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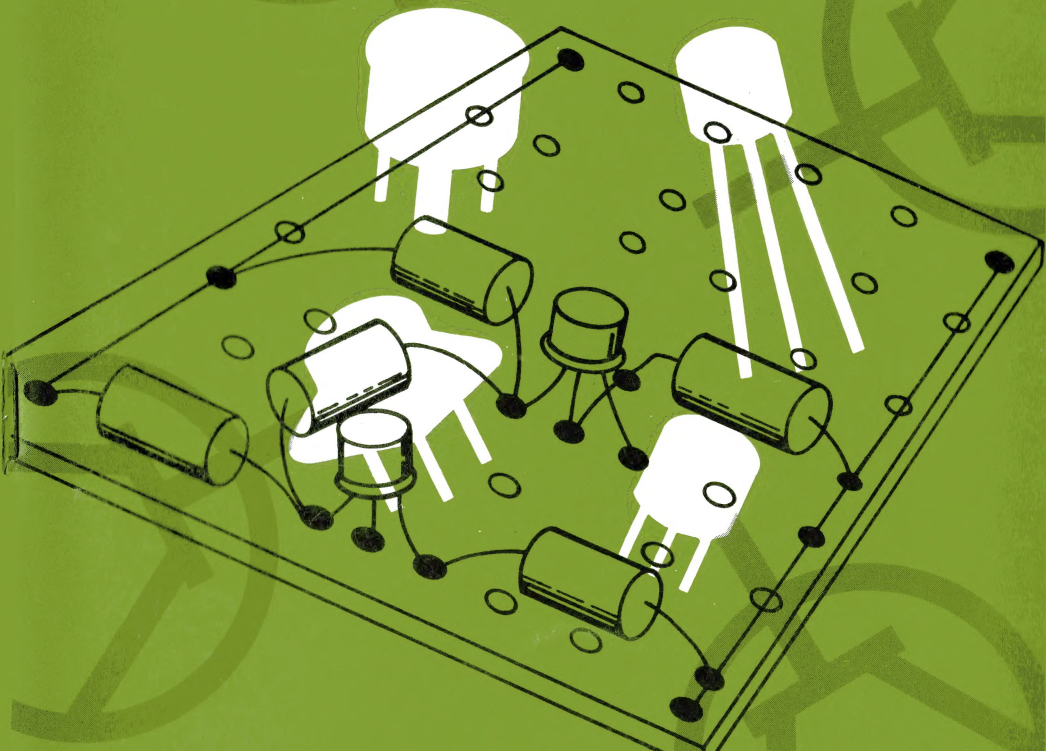
introduction to TRANSISTORS & TRANSISTOR PROJECTS



Introduction to

TRANSISTORS & TRANSISTOR PROJECTS

by

Forrest M. Mims, III

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PREFACE

The development of the transistor is one of the great accomplishments of the twentieth century. The miniaturization resulting from applying transistors in electronic circuitry has made possible everything from practical space flight to hearing aids small enough to fit completely in the ear. Furthermore, transistor technology has resulted in the development of a host of new and useful electronic devices and the industries to manufacture them. Integrated circuits, light-emitting diodes, silicon controlled rectifiers, and scores of other semiconductors all owe their present state of development to semiconductor processing techniques used to make transistors.

This book is intended to show the electronics experimenter how the transistor was developed, how it is manufactured, and how it works. The heart of the book is the description of transistor operation, for the experimenter who masters these fundamentals is well on the way to being able to design his own electronic circuits.

The more ambitious reader will want to solidify the transistor principles of the main text by assembling some of the construction projects at the end of this book. The projects are easy to assemble and inexpensive. Besides providing an excellent introduction to transistor circuits, each of the projects has practical applications as well.

You can continue learning about semiconductor electronics by reading other books on transistors. Besides providing both an entertaining and educational hobby, a working knowledge of semiconductor electronics can play an important role in influencing vital career decisions.

FORREST M. MIMS, III

CONTENTS

CHAPTER 1

THE AMAZING SEMICONDUCTORS

The development of semiconductor electronics has affected the lives of everyone reading this book. Indeed, much of the world's population is dependent on semiconductors for everything from music and news to weather forecasting.

This modern technological revolution is the result of the transistor and other semiconductor electronic devices. The large scale manufacturing of inexpensive, efficient transistors has helped place miniature radios in the hands of a substantial part of the world's population. Transistors and other semiconductor devices have made possible the important weight reductions necessary for practical space travel. In fact, as we will see later, practically every aspect of modern life is influenced in some manner by semiconductor technology.

This book has been planned to provide the reader with a good background in both transistor theory and operation. So that the significance of these little semiconductor devices will not go unrecognized, their fascinating history and many of their applications will also be discussed.

THE FIRST SEMICONDUCTORS

The role played by solid-state electronic devices before the vacuum-tube era is generally not recognized. However, the importance of early devices such as the coherer and galena crystal detector should not be underestimated.

In 1901, five years before Dr. Lee de Forest was granted a patent for developing his first electron tube, Guglielmo Marconi was transmitting signals across the Atlantic ocean with a

25,000-watt spark transmitter and a coherer detector. Merely a glass tube filled with metal filings, the coherer was normally a poor conductor of electricity. But the presence of a small electrical signal reoriented the filings so that they readily conducted electricity. The change in resistance could be easily detected by a meter.

The coherer was inefficient (it had to be "decohered" between signal pulses with a tap from a clockwork mechanism) and not nearly as sensitive as modern electronic detectors, but it played a vital role in the early development of radio.

The success of the rather crude coherer stimulated the development of dozens of new types of detectors. Some of them operated on principles as diverse as magnetism, electrolysis, and even flame. But the most practical ones turned out to be the mineral crystal detectors—the first semiconductors.

Crystal detectors became the most important receiving device from about 1906 to after World War I. Though de Forest's electron tubes had evolved into amplifying devices with the addition of a third electrode, the grid, they were unreliable and their operation was not well understood.

The crystal detectors employed a "cat-whisker" arrangement, similar to the one shown in Fig. 1-1, in order to find a good, sensitive spot on the crystal. Developed and patented by Greenleaf Pickard, cat-whisker crystal detectors used any of more than 200 different mineral crystals. The most popular, however, were galena, silicon, and *Carborundum.*

Operation of the cat-whisker crystal detector was so simple and reliable that thousands of amateur and professional radio enthusiasts latched onto the device. Communications during

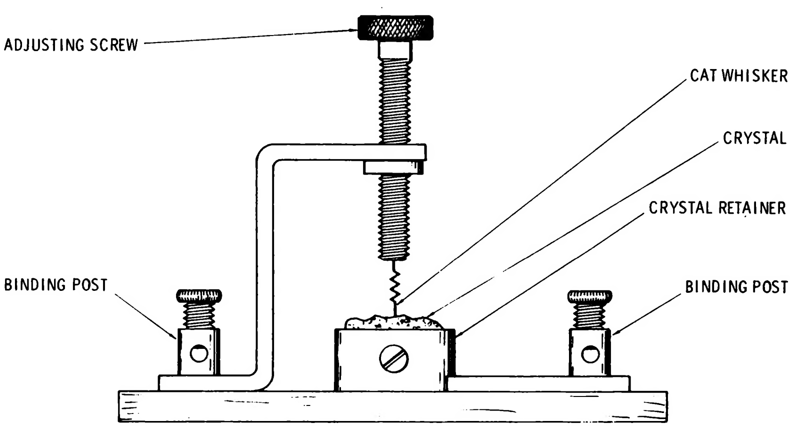


Fig. 1-1. Cat-whisker crystal detector (1906).

World War I and amateur link-ups were made possible by the reliability of the simple device. Crystal radios became popular receiving devices in many homes of the era and homemade versions were built by many school boys.

The success of crystal detectors stimulated early work with crystal amplifying devices. In 1923, a book by P. J. Risdon called *Wireless* was published in England. Risdon described the work of O. V. Lossev in developing a crystal device capable of amplification. The book reported: "Several (crystal) combinations have been found to possess this property, one being zincite used in conjunction with a steel point. It must not, of course, be supposed that the crystal itself magnifies—it merely serves, as a valve functions, to impress fluctuations in received oscillations on an electric current." The text went on to note that "the further development of this discovery may revolutionize broadcast reception" because of the low cost of the crystal and the fact low voltage batteries could be used. Written a full quarter century before the "invention" of the transistor, these words are remarkably prophetic.

Several other workers of the period also developed semiconductor amplifying devices, the most notable being Julius E. Lilienfeld. First invented in 1925, Lilienfeld's device bears an uncanny resemblance to the modern field-effect transistor.

Shown in Fig. 1-2, the device consisted of a small, glass plate which was coated with two strips of a conductor such as gold or silver. The glass plate was then cut in half and a very thin aluminum-foil electrode was inserted between the two halves. The plate was then reassembled, connection wires were fastened to the three electrodes, and a semiconductor coating was applied over the assembly. As we will see in Chapter 4, this is in principle virtually identical to the construction of a modern field-effect transistor.

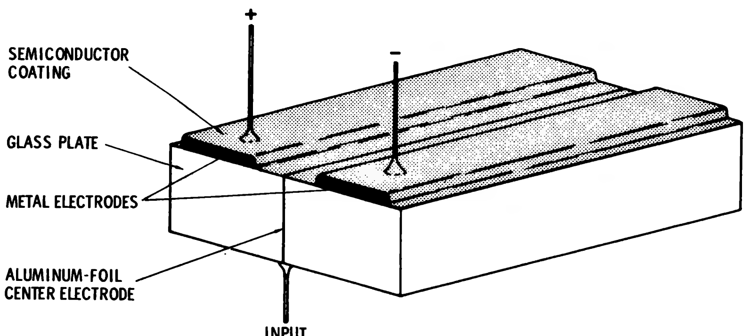


Fig. 1-2. Solid-state amplifier (1925).

THE ELECTRON-TUBE ERA

The semiconductor diodes and transistorlike devices which followed the cat-whisker detectors were generally regarded as curiosities. The theory of the period was inadequate to explain how they operated, and important advances in electron-tube technology lifted interest away from semiconductors.

It is unfortunate that the early semiconductor work was dropped, for suitable support might have resulted in the modern transistor being invented twenty years earlier. However, the importance of the electron-tube developments should not be underrated since it was the circuitry developed for electron tubes which was first adapted to accommodate the transistor applications.

Going back to 1912, we find that de Forest's invention of the triode electron tube, the *audion* as he called it, was having problems. Few people of the time, technical or otherwise, realized the significance of de Forest's invention. The company formed to develop and market the device was charged by the Federal government with using the mail to defraud. Dr. de Forest himself was not found guilty of the alleged offense, but three of his co-workers were sentenced to serve jail terms. In a tragically naive move, the court upheld the government prosecutor's charge that, "This is a company incorporated for $2,000,000 whose only assets were de Forest's patents in a strange device which he called the audion and which device had proven worthless, even as a lamp."

Though beset with legal problems and sometimes ridiculed by his peers, de Forest worked all the harder and soon succeeded in improving the audion to the point where it could be used in practical applications. In 1912, he demonstrated to American Telephone and Telegraph (AT&T) a three stage, audion amplifier which had a voltage gain of about 125. The company was impressed and bought some of the rights to the invention for $50,000. The AT&T people planned to use the amplifiers as repeaters—circuits to beef up weak, telephone signals being transmitted over lengthy wire hookups. But the audions worked so well, that the company bought the radio rights of the tube a few years later for $90,000.

Dr. de Forest's work was the beginning of the vacuum-tube era. Edison and Fleming had made pioneering discoveries about the actions of electrons in a vacuum, but de Forest had developed practical devices. By World War II, the vacuum tube was well established as the backbone of the American electronics industry.

THE TRANSISTOR

During World War II semiconductor research expanded, somewhat due to the advantages of using solid-state diodes as microwave detectors. Then, in 1948, Drs. John Bardeen and Walter Brattain of Bell Telephone Laboratories developed what was to become the first successful semiconductor triode. Since they called their germanium diodes *varistors,* and since this new device used a varistor with a third connection in order to transfer signals, the word *transistor* (TRANSfer varISTOR) was coined to name their development.

The first commercial transistors used the same cat-whisker technique first applied to crystal diodes by Pickard more than forty years earlier. Called point-contact transistors, the devices consisted of a small chip of germanium about 0.06-inch square and 0.02-inch thick, connected to a metallic support. As shown in Fig. 1-3, the support formed one of the three electrodes, the base, which was connected to the chip. The remaining two electrodes consisted of tiny phosphor-bronze wires spot-welded on two upright leads. The free ends of the tiny wires were placed a few thousandths of an inch apart on the top surface of the germanium chip. The entire assembly, which was quite fragile, was encased in a small metal or plastic container from which emerged the three connection leads. In this manner the delicate point contacts were protected from being displaced.

Because its frequency response was relatively good, the point-contact transistor was at first rather successful. However, the inherent disadvantages of the device soon turned attention to newer kinds of transistors. The most notable problems included undesirable interactions and heating at the contact points due to high contact resistance. Another disadvantage was the extreme difficulty in making point-contact transistors with engineered characteristics.

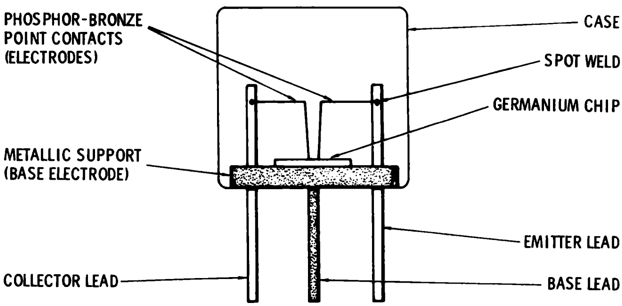


Fig. 1-3. Point-contact transistor (1948).

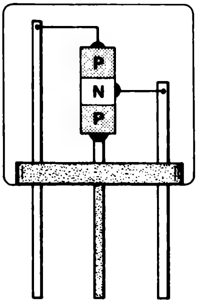


Fig. 1-4. Junction transistor (1952).

Dr. William Shockley solved many problems of the point-contact transistor with his invention of a transistor which used internal connections instead of the temperamental cat whiskers. Shockley's *junction* transistor is the basis of most modern semiconductor technology.

Fig. 1-4 shows an outline representation of a typical junction transistor. The simplicity of the device results from replacing the point contacts with direct interfaces of the semiconductor material making up the transistor. The result is a sturdy device which operates in a manner far more predictable than the point-contact transistor.

For a few years, point-contact transistors found limited use in high-frequency circuits, since their frequency response was superior to that of junction devices. Improvements in technology, however, eventually brought the junction device frequency response up to higher levels, and the old point-contact transistors are now extinct.

The advent of the practical transistor caused a veritable explosion in the young semiconductor field. A whole new industry

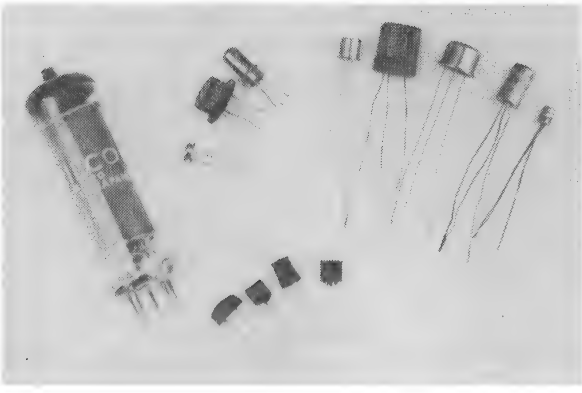


Fig. 1-5. Tube/transistor size comparison.

was established to manufacture transistors. Predictions about the quick downfall of the electron tube were rampant. The size comparison of a transistor and a typical miniature electron tube in Fig. 1-5 vividly illustrates the space reduction made possible by the transistor. While the electron tube was not replaced as quickly as the new semiconductor industry hoped, transistors made a firm foothold in electronics, and now tubes are reserved more and more for special applications which demand characteristics obtainable only with special purpose electron tubes.

OTHER SEMICONDUCTOR DEVICES

The transistor industry began making dozens of new discoveries about the unique properties of semiconductors in the first few years after the point-contact transistor was developed. The discoveries paved the way for a host of new kinds of transistors and other semiconductor components, with hundreds of applications. The space available in this text limits a complete discussion of all these new devices, but some of them are so important to modern electronics that they will be described. Since there are so many important classes, an entire chapter is reserved for describing the major transistor types.

Improvements in diode technology make up one of the biggest advances in nontransistor, semiconductor devices. Zener diodes, which have the important ability to regulate voltage, are frequently used in power supplies. With commonly available zener diodes, the circuit designer can quickly insure that proper voltages are impressed across any part of a circuit. Another important semiconductor is the Esaki diode, named after its inventor. This diode employs an electron tunneling effect to achieve an exceptionally high frequency response. Often called the tunnel diode, Esaki diodes can be used in very simple radio-frequency oscillators. high-frequency amplifiers and logic circuits. Because of their critical operating voltage requirement, their use is generally restricted to specialized circuits.

Perhaps the most unique diodes are those which have useful optical characteristics. By using specially prepared semiconductors such as gallium arsenide and gallium arsenide phosphide, diodes can be made which emit visible and infrared light. These light-emitting diodes (LEDs) are finding use in light-beam communication systems for both voice and data transmission. Because of their exceptionally long lifetime, LEDs are being used as indicator lamps. And because of their

very small size and low current requirements, arrays of LEDs are being used as digital readouts in test equipment, electronic calculators, and even watches.

Years before practical LEDs were commercially available, a variety of light-sensitive transistors and diodes were made available. It was recognized that transistor junctions responded to light and by 1952, J. N. Shive had developed a reliable phototransistor. A point-contact device, Shive's light-sensitive "M-1740 photocell" was the predecessor of the literally dozens of types of photodiodes and phototransistors available today.

Another kind of silicon light detector developed in the 1950s is the silicon solar cell. Invented by the productive scientists at Bell Telephone Laboratories, the solar cell consists of a wafer of n-type silicon, coated with a thin, p-type layer. Electrical contacts are attached to both sides of the device. When the cell is exposed to light, a flow of electrons takes place and the cell acts very much like a dc (direct-current) battery. Silicon solar cells are widely used to power electronic systems aboard satellites and other spacecraft. They have even been used to operate transistor radios, hearing aids, and clocks.

Another semiconductor device developed as a result of transistor technology is the silicon controlled rectifier (SCR). Consisting of four layers of semiconductor material, SCRs are the solid-state equivalents of thyratrons. Most SCRs have three terminals. Normally, current does not pass between two of the three terminals, but a small voltage pulse applied to the third terminal turns on the SCR and allows it to conduct.

The SCR is an exceptionally versatile device. It has replaced the electromechanical relay in many applications and is widely used in power-control circuits.

There are other important semiconductors which owe their development to the advent of the transistor. There are silicon temperature sensors as small as a pencil point, highly-sensitive infrared detectors, and a bewildering variety of exotic microwave and even laser diodes. All of these devices may have ultimately been invented, but there is no doubt the arrival of the transistor speeded their development.

INTEGRATED CIRCUITS

While Bell Telephone Laboratories can claim credit for the first transistor, Texas Instruments and Fairchild were the first firms to make an integrated circuit. For the first time in the history of electronics, individual components such as transistors, diodes, capacitors, and resistors could be formed within a

single, tiny chip of semiconductor. The implications for miniaturization were immediate and development was soon being given a hard look by practically every company in the transistor business.

At first, integrated circuits (ICs) contained only a few individual components, but advances in processing techniques used to make the chips eventually reached the point where dozens and even hundreds and thousands of individual components were formed in a single, tiny block of silicon.

While integrated circuits are replacing transistors and other discrete components in many applications, this does not necessarily mean that the transistor will one day become as extinct as the coherer. On the contrary, transistors form the nerve centers of ICs.

A LOOK AHEAD

As our discussion may have indicated, the exploding technology of modern electronics will no doubt bring about many other interesting and useful developments. The emerging field of optoelectronics is just one such achievement. Already an entirely new vocabulary is being evolved just to describe this rapidly expanding field of electronics, and LEDs, laser diodes, semiconductors displays, and optoelectronic isolators are finding uses in many practical applications.

The biggest electronics revolution of all may well be in the field of microminiaturization. New kinds of integrated circuits employing metal-oxide semiconductors (MOS) cram literally thousands of diodes, transistors, and resistors onto single tiny chips of silicon in a technique called large-scale integration (LSI). The development of these new LSI MOS ICs has been exceptionally rapid for the potential markets are great. One of the biggest is the electronic calculator field. By the early 1970s, several companies, many of them new, were in the business of selling calculators ranging in price from well under $100 to more than several thousand dollars. While the lower priced models are great for the student and homemaker, the more expensive versions provide all the capabilities of a true desktop computer. Before the end of the 1970s, we can expect to see even more of these math machines at prices practically anyone can afford.

The LSI circuits are not limited to electronic calculators. Several watch companies have developed watches which use tiny LSI chips to convert the ultrafast precision vibrations of an electronically pulsed quartz crystal to the much slower

pulses required to drive the hands (or operate the LED or liquid crystal display) of a super accurate watch.

These are just a few of the applications already arising from recent developments in the field of solid-state electronics. If these and other recent breakthroughs in this fast growing field continue to occur at their present pace, we can expect to see even more spectacular applications of semiconductor electronics in the future.

CHAPTER 2

TRANSISTORS AND HOW THEY WORK

An understanding of some basic concepts in atomic structure will greatly simplify an explanation of how transistors work. An atom is made up of two primary parts, a positively charged nucleus and a surrounding cloud of negatively charged electrons. The nucleus of a typical atom is ordinarily a complex arrangement of subatomic particles, and it is fortunate for the semiconductor physicist that transistor action involves mainly the electrons.

The cloud of electrons surrounding the nucleus can be thought of as containing several energy levels, each with a fixed number of electrons. These levels are often referred to as *shells* or *bands*, since the electrons within them surround the centrally located nucleus. Each shell has the capability of holding a fixed number of electrons.

The inner shells of an atom are generally very stable since they are occupied by a full complement of electrons. However, the outer shell may not have its full complement. This *valence* shell has the tendency to permit its electrons to cooperate with the valence electrons of other atoms so that one or both atoms can fill its outer shell with the required number of electrons. This and other types of events form bonds between two or more atoms to create a *molecule.*

A good example of such a combination of atoms is ordinary table salt, sodium chloride. Chlorine has seven electrons in its valence shell but needs eight for a full complement. Sodium, on the other hand, has but one electron in its valence shell—and it is easily dislodged. When a chlorine atom collides with a sodium atom, the latter gives up its sole valence electron to the former.

Since the chlorine atom is now negatively charged and the sodium atom is positively charged, the atoms attract one another in an *ionic bond* to form the sodium-chloride molecule.

Another kind of atomic bonding is the *covalent bond.* This type of bond occurs when a group of atoms literally share their valence electrons so that they all will have a full valence shell. Semiconductors often consist of atoms held together by covalent bonds.

Now that we know something about the role of electrons in forming molecules it's easy to see how they play such an important role in electricity. As we have just noted, electrons in the outer shell of an atom are far more mobile than the relatively stable electrons of the inner shells. This is particularly true if there are less than four electrons in the outer shell. If an electron source, for example a battery, is connected to a material whose outer shell has only a few electrons, the electrons readily move from the outer shell of one atom to the next and so forth. The result is a flow of electrons, or an electrical current.

CURRENT

The orderly movement of electrical charges through any material is termed a *current.* Since good conductors such as silver and copper have but one electron in their valence band, it is believed that current in metals is by a movement of electrons. In a semiconductor, however, current can also be thought of as a movement of positive charges.

Normally an atom has no electrical charge since the number of its electrons and protons are equal. But when an electron moves from one atom to another, it leaves behind an atom which now has a positive charge. It is convenient to refer to the term *hole* as the place the electron once occupied. Since an atom with a hole is positively charged, we can think of the hole as being a positive particle. Since electrons moving through a semiconductor from one point to another leave behind a string of holes, we can think of the holes as moving in a direction opposite that of the electrons.

This concept is not as confusing as it may seem if we compare it to a glass tube filled with water and having a small bubble at one end. When the tube is inverted, we say the bubble has moved from one end to the other—when actually it is the water which has moved since the bubble is an empty spot or hole in the tube. Just as the bubble corresponds to the hole, its movement symbolizes the flow of positive particles or holes in

a direction opposite that of electrons. This concept of both hole and electron flow, can greatly assist one in understanding transistor action.

SEMICONDUCTORS

Chapter 1 noted that transistors are made from materials called semiconductors. As the name implies, a semiconductor is a material which is neither a good nor bad conductor of electricity. While good conductors have from one to three electrons in the valence shell, semiconductors have four. Insulators, materials which do not normally conduct electricity, have more than four valence electrons. The relation of conductors, insulators, and semiconductors to one another is shown in Fig. 2-1.

The semiconductors most commonly used in transistors are germanium and silicon. Though both have four electrons in their valence shells, each material is characterized by its own unique properties.

Since both germanium and silicon have but four valence electrons, their atoms tend to form stable crystals whose structures permit neighboring atoms to share electrons with one another. This type of atomic cooperation is the covalent bond we discussed earlier.

A simplified diagram of covalent bonding in germanium material is shown in Fig. 2-2. The actual structure of the crystal is three-dimensional and not flat as shown here. The uniform distribution of atoms forms a crystal which is similar in nature to the crystalline structure of a diamond. This very uniform structure of germanium (and silicon) is very important to the formation of practical semiconductor electronic components.

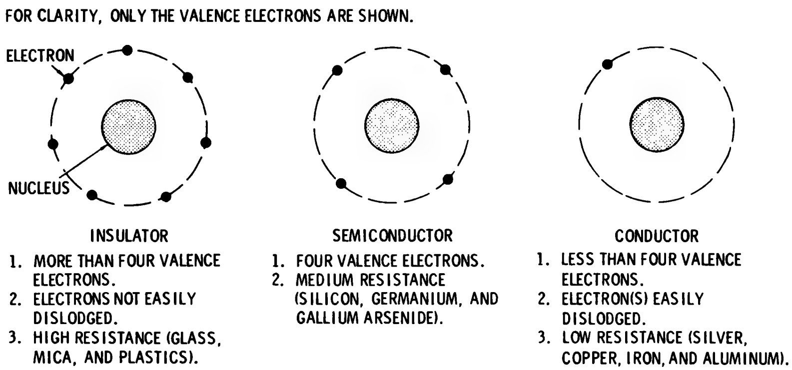


Fig. 2-1. Comparison of an insulator, semiconductor, and conductor atom.

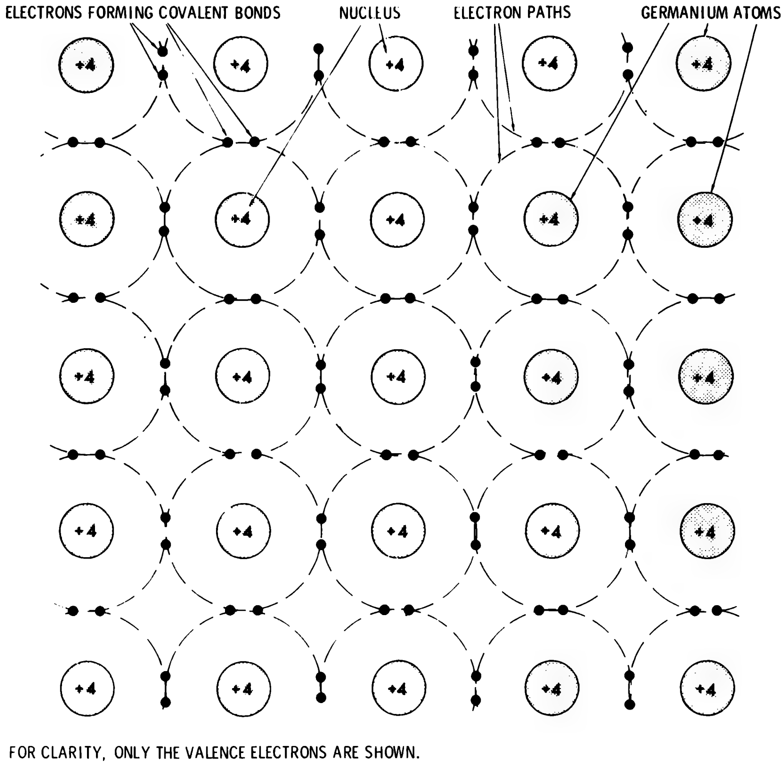


Fig. 2-2. Covalent bonding in germanium material.

SEMICONDUCTOR TAILORING

While extremely pure semiconductor material is required for the formation of semiconductor components, the devices will not operate as planned unless the semiconductor is made a better electrical conductor. The big advantage of a semiconductor material is that the careful addition of impurity atoms can reduce the electrical resistance of the material and permit it to conduct electricity better.

At this point the reader might ask why it is necessary to go to all the effort to make a very pure, intrinsic batch of silicon or germanium and then intentionally contaminate it so that it conducts electricity better. A copper wire is a lot easier to make and it already conducts well.

The answer is that proper selection of impurity atoms results in a semiconductor which can conduct electricity by either positive or negative charges. When a positive semiconductor

material is formed directly adjacent to a negative semiconductor material the resulting junction has the unique property of permitting an electron flow in only one direction. The result is a sort of one way electrical valve known as a *diode.*

We'll discuss the diode in more detail later, but first it is important to see how the addition of impurity atoms make a semiconductor either positive or negative.

We know that pure germanium is electrically neutral since there is an equal number of electrons and protons scattered through the crystal. We also know that germanium atoms lack a full complement of valence electrons and, therefore, we can mix in some foreign atoms that will form covalent bonds with the germanium atoms. In Fig. 2-2, the covalent bonds were provided by the germanium itself. Therefore, to obtain a sample of negative germanium, all that is required is to add impurity atoms which have five valence electrons, one more than required for the formation of covalent bonds. Typical impurity atoms with the required five valence electrons are

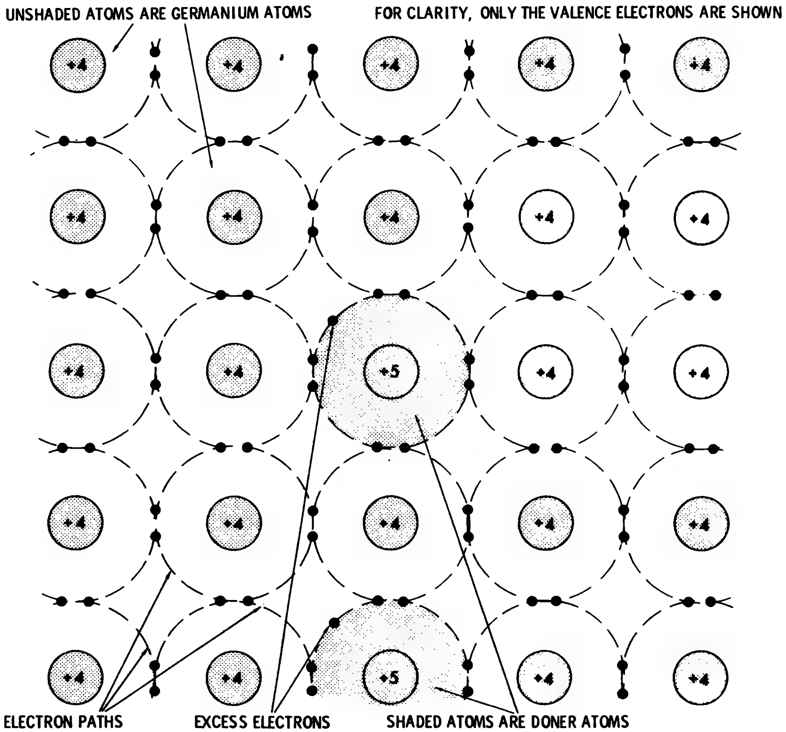


Fig. 2-3. Germanium crystal (n-type).

phosphorus, arsenic, and antimony. Since these elements donate electrons, they are referred to as *donors*.

Referring to Fig. 2-3, we see a diagram representing the result of adding impurity atoms containing five valence electrons to germanium. A covalent bond is formed and the impurity atoms are held in a stable crystal lattice. Thereby, with the additional electrons, the semiconductor is then said to be a negative or n-type crystal.

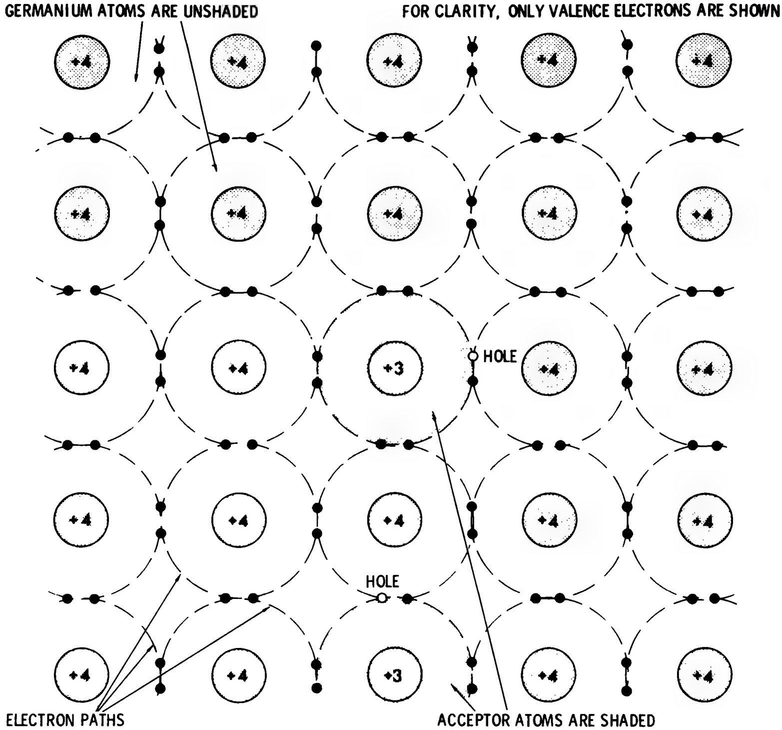


Fig. 2-4. Germanium crystal (p-type).

Positive or p-type semiconductor is formed by addition of an impurity which is deficient in valence electrons. If, for example, we add atoms which have only three valence electrons to germanium or silicon, partially complete covalent bonds would be formed. Referring to Fig. 2-4, we see that the resulting atomic structure has an electron deficit and is hence positive or p-type.

Typical elements whose valence shell contains three electrons are gallium, indium, and aluminum. Since these elements ac-

cept electrons from the host semiconductor crystal, they are called *acceptors*.

SEMICONDUCTOR CURRENT

Current through a semiconductor is usually defined according to the polarity of the material. For example, since n-type material has an excess of electrons, current flow is by means of electrons. P-type material achieves a flow of current by means of its surplus holes. In a semiconductor the charge which carries the current flow is called the *majority carrier*. The name comes from the fact that either electrons or holes outnumber one another and are therefore in the majority. Majority carriers in an n-type semiconductor are electrons, and holes are the majority carriers in a p-type material.

As the name implies, *minority carriers* designate which charge, positive or negative, is outnumbered by the other. Minority carriers are holes in n-type material and electrons in p-type material.

Though semiconductors are made more conductive by the addition of impurities, it's interesting to note that pure germanium has a much lower resistance than pure silicon. This means transistors made from the two semiconductors can have different properties.

The reason germanium's resistance is so much lower than that of silicon is that germanium has far more conduction electrons. In actual numbers, germanium has 2×10^{13} conduction electrons per cubic centimeter while silicon has only about 2×10^{10}. This difference in the number of conduction electrons results in silicon and germanium transistors having somewhat different properties; several of these differences will be described later.

PHYSICS OF THE DIODE

A diode is an electronic component which acts very much like a one-way valve since it permits current to flow through it in one direction but not the other. Since in some respects a transistor can be thought of as two diodes back to back, it's appropriate to use the diode to introduce the transistor.

As you will recall from Chapter 1, diodes have been with us for some time. In fact, a good many modern diodes utilize the same cat-whisker method employed by Pickard's 1906 silicon detector. All transistors and most diodes, however, have eliminated the cat whisker in favor of a sturdier, more reliable type

of construction where the diode action takes place in a solid block of semiconductor composed of both p- and n-type material.

A typical semiconductor diode is shown in Fig. 2-5. The border between the n- and the p-region is called the *junction* and is an integral part of the material. While it is convenient to think of each half as a separate block of semiconductor, it is important to remember that the diode is a single block of material whose ends have been given opposing polarities by the addition of carefully controlled amounts of impurities. The diode would not operate properly if a block of n-type material was simply pressed against a similar block of p-type material, because of the high resistance at the interface of the blocks and other reasons.

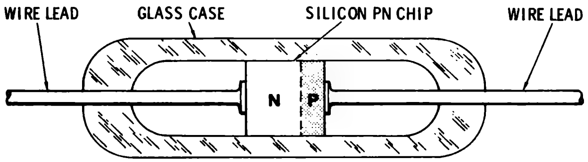


Fig. 2-5. Construction of a typical pn junction diode.

The way a diode opposes current flow in one direction and permits it in the other, is quite interesting. The phenomenon depends on the fact that oppositely charged particles attract one another while like charges repel. If we connect a negative source of current to the p-side of the diode, electrons injected into the material will be repelled by the electron rich n-region on the other side of the junction. Since those electrons which are injected into the diode cannot cross the *potential barrier* formed by the junction, there is no current flow.

If we reverse the connections to the diode so that the negative side of the battery is connected to the diode's n-region, the electrons being injected into the material are not repelled at the junction. In fact, the injected electrons repel the excess electrons already in the n-region toward the junction where they readily cross over to fill the abundant concentration of holes which exist on the p-side. Since the electrons cross the junction, there is a current flow from the negative terminal of the battery to its positive terminal.

While we have been speaking of current in terms of electrons, it's important to remember that there is a flow of holes as well. As electrons cross over the junction to combine with holes, a new supply of holes flow toward the junction to replenish those which are filled by electrons. The net result is a

flow of electrons and holes from opposite sides of the diode to the central junction region. The holes, of course, move in a direction opposite that of the electrons.

So that the rectifying action of a diode can be readily identified, the symbol shown in Fig. 2-6 is used to identify the p- and n-regions in an electronic circuit diagram. The p-region is called the *anode* and the n-region the *cathode.*

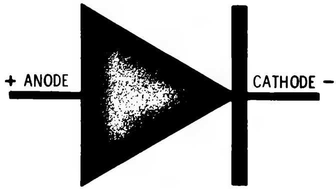


Fig. 2-6. Diode schematic symbol.

DEMONSTRATING DIODE ACTION

It is one thing to read about diode action in a book, but it is quite another to actually check the theory with a simple experiment. All that is needed to perform the experiment is an inexpensive diode, a small light bulb, and a 9-volt battery. If a germanium diode is used, a resistor with a value of about fifty ohms should be used to compensate for the lower resistance of the diode. Otherwise, the lamp or the diode might be damaged by excessive current flow. Using clip leads so the diode's con-

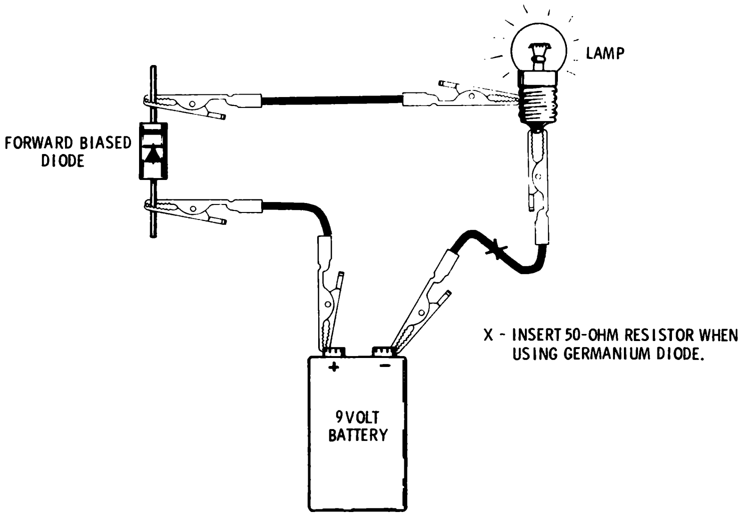


Fig. 2-7. Experiment to show the biasing action of a diode.

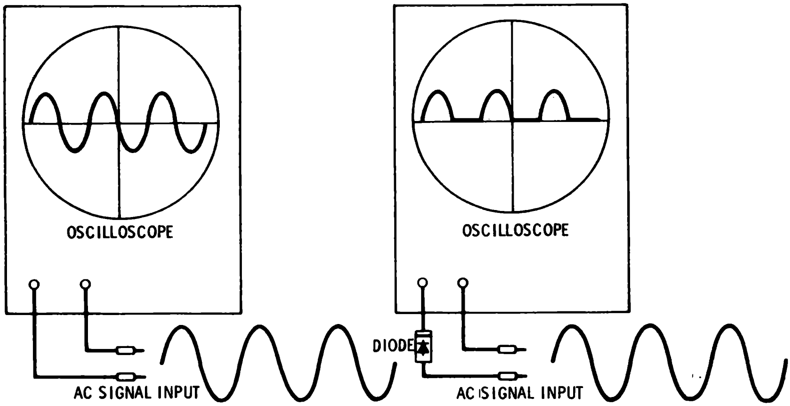
nections can be easily reversed, set up the experiment as shown in Fig. 2-7.

When the diode's anode is connected to the positive terminal of the battery and the diode's cathode is connected to the negative terminal of the battery, current will flow across the diode's junction, the lamp will light, and the diode is said to be forward biased.

Next, reverse the diode's connections. Since there is no current flow, the lamp will not light and the diode is said to be reverse biased.

A very interesting variation of this simple experiment employs a *light-emitting diode* (LED). This kind of diode, which is available from Radio Shack for somewhat more than the price of a standard diode, is made of gallium arsenide or gallium arsenide phosphide, and has the property of emitting either visible or infrared light when forward biased. Actually, ordinary silicon and germanium diodes (and even transistors) emit some infrared when forward biased, but the amount is so tiny as to be almost undetectable without special instruments. Photons of light are emitted as electrons crossing the junction give off the energy required to propel them over the junction's potential barrier.

The properties of a diode are very valuable in many electronic circuits. Most electronic equipment (radios, televisions, test equipment, etc.) require direct current (dc); diodes perform the important role of converting the ac to dc. In Fig. 2-8A an alternating current is shown on an oscilloscope as a sine



(*A*) *Alternating current applied to scope.* (*B*) *Alternating current applied to diode and scope.*

Fig. 2-8. Rectifying action of a diode.

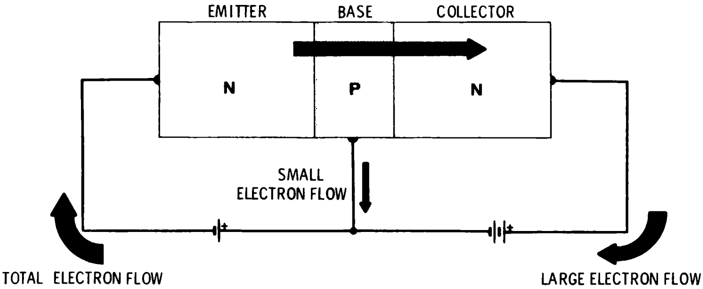


Fig. 2-9. Current flow in an npn transistor.

wave. In Fig. 2-8B a diode inserted in the ac circuit has blocked the negative part of the current but is passing the positive part. The pulses of positive current can be smoothed out by a capacitor and used to operate equipment which requires dc.

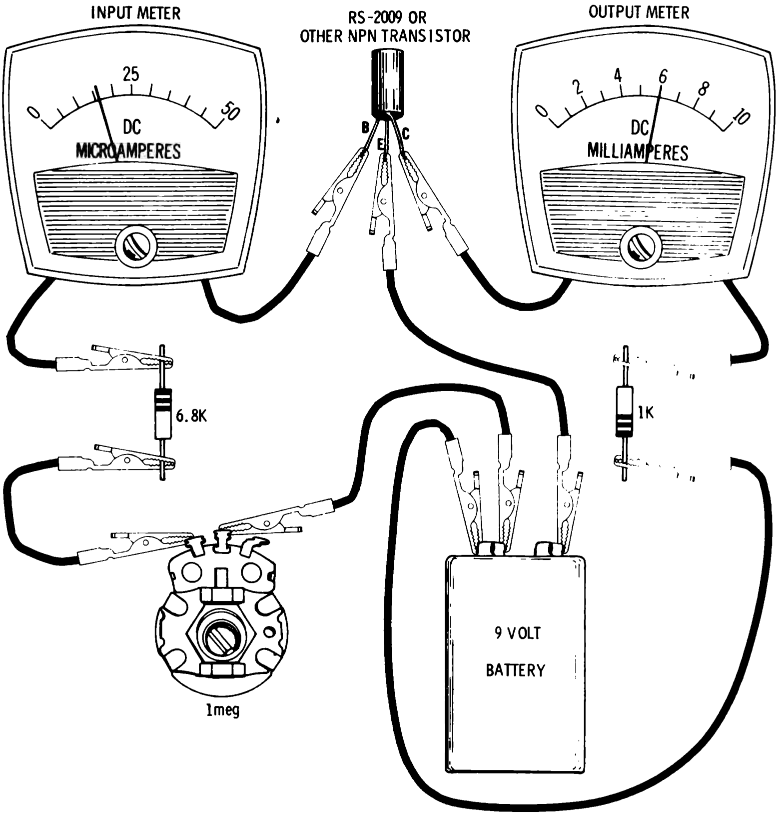


Fig. 2-10. Amplifier demonstration circuit.

PHYSICS OF THE TRANSISTOR

By now you should have a reasonably good understanding of what can be done with a single pn junction. While diodes made with a pn junction are inexpensive and very easy to use, there is no way to control the amount of current passing through them. There is either a flow of current or there is not.

By adding a third region of n- or p-material to the proper part of a diode, we can set up a situation where the current flow can be easily controlled. The device which results from this modification of a junction diode is the transistor.

To see how this is done, refer to Fig. 2-9. Two voltage sources are connected across the sandwich of three semiconductor layers forming the transistor. Because of the relative positions of the three layers, the transistor is a npn.

The fact that a large amount of current through a transistor can be controlled by a very small current is what makes the transistor so important for this is the principle of amplification. An electronic amplifier is a device which controls a large force with a small force. Contrary to popular thought, amplifiers do not magnify a signal but use a signal to control a much larger voltage or current.

CHAPTER 3

HOW TRANSISTORS ARE MADE

While the operation of an electron tube depends on the flow of current through a vacuum or gas, transistors require a chip of specially prepared semiconductor for proper operation.

It is relatively easy to evacuate an electron tube, but the preparation of semiconductor material pure enough for use in transistors is not nearly so simple. The problem is compounded by the fact that various parts of the individual chips used for transistors must be made either n- or p-type. This chapter will describe the techniques manufacturers have developed for obtaining pure semiconductor material and fabricating it into transistors.

CRYSTAL GROWING

While silicon and germanium are found in nature, they are always mixed with other elements and are never pure enough for use in transistors and other semiconductors. Very pure semiconductors are needed so that carefully controlled amounts of impurities can be added to tailor the material for specific types of transistors. In addition to purity, the semiconductor must be a singular crystal in nature.

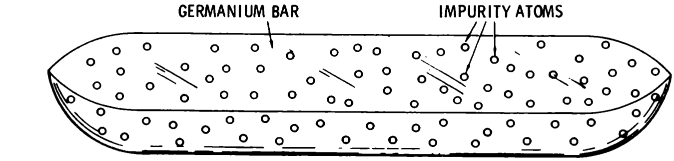
Several techniques are employed to obtain high purity semiconductors. The most common for germanium is called *zone refining* and is shown in Fig. 3-1.

The zone refining purification technique capitalizes on the fact that crystal impurities tend to stay suspended in a molten rather than solid material. In operation, a bar of germanium is placed in a furnace where a series of radio-frequency (rf) heating coils melt layers in the bar as it is slowly pulled

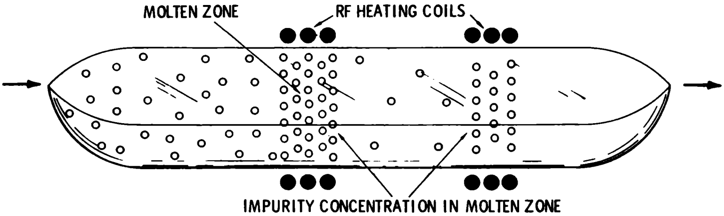
through the furnace. By subjecting the crystal to zone refining, the impurities tend to collect at one end of the material giving a final purity level of about 1 part in 10^{10}.

Because of its high melting point (2588° F), silicon is not purified by the zone refining process. Other problems, such as the possibility of contamination from the boat used to hold the molten material, are the reason silicon is almost always purified chemically and not thermally. Fortunately, available chemical techniques give impurity concentrations of only about 1 part in 10^{10}.

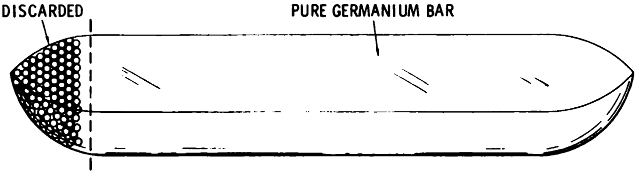
When high purity germanium or silicon is obtained, it must be formed into a crystalline structure with no internal imperfections or defects. Imperfections may take several forms including point, line, and plane defects. All these imperfections are a result of deformities in the semiconductor's structure and can be compared to stacks of blocks. If the blocks are neatly stacked, the crystal structure is perfectly formed. But if extra blocks (point defect) or slippage between rows of blocks (line and plane defects) are present, the structure is imperfect. Two crystalline defects are shown in Fig. 3-2.



(A) Germanium bar containing impurities.



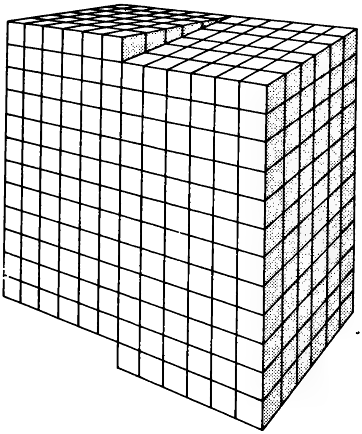
(B) Germanium bar traveling past heat coils.



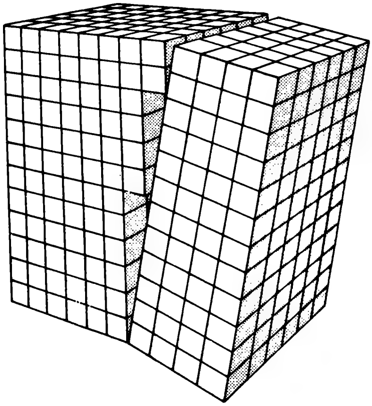
(C) Refined bar of germanium.

Fig. 3-1. Zone refining of germanium.

To achieve a prefect crystal, the semiconductor material is melted and grown into a single crystal. Such a crystal consists of one uniform structure and, ideally, no interrupting imperfections.



(*A*) *Screw dislocation.*



(*B*) *Plane or boundary defect.*

Fig. 3-2. Two common crystalline defects.

Single crystal germanium is often grown in a crystal-pulling furnace. Shown in Fig. 3-3, the furnace consists of a crucible surrounded by rf heating coils. A shaft, which is connected to a mechanical system which both rotates and moves in and out, is installed in the furnace assembly to provide a point for crystal formation. Argon or some other inert gas is pumped through the furnace to keep out impurities. Highly purified germanium is placed in the furnace and heated until it melts. When the temperature of the melt has been properly adjusted, the shaft is lowered so that a small "seed" crystal attached to it is immersed in the liquid germanium. The shaft is then rotated (to stir the melt and encourage uniform crystal formation) and pulled upward at a rate of no more than a few inches every hour.

As the seed crystal leaves the melt, the small amount of molten germanium which wets its lower portion is cooled and returned to a solid state. The solidified material takes on the same crystalline orientation as the original seed. Eventually, a crystal up to ten-inches long and one-inch in diameter is pulled from the melt.

Appropriate impurities are added to the melt to obtain p- or n-type germanium. Since the dopants tend to stay behind in

the molten germanium, more impurity material is added to the melt than eventually ends up in the finished crystal.

Silicon's very high melting point and susceptibility to contamination during crystal growth are reasons why germanium was first perfected for use in transistors. Silicon can also be formed into large single crystals by using the pulling process just described. Modifications, however, are necessary to prevent the dopants from vaporizing in the presence of the very high furnace temperature required to melt the silicon.

Another technique of forming single crystal silicon is similar to the zone refinement method used to purify germanium. A rod of pure polycrystalline silicon is mounted inside a hollow quartz tube which is sealed at both ends. A movable rf heating coil then slowly slides up the tube from bottom to top. As the heating coil applies heat to the silicon bar or ingot, a thin section of the bar melts. Therefore, as the coil moves up the tube the molten section crystallizes with the orientation of the seed

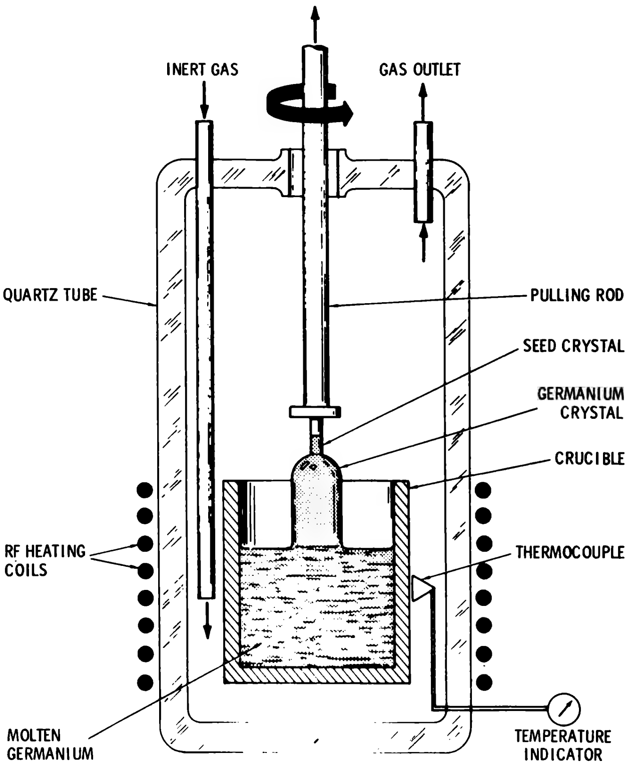


Fig. 3-3. Germanium crystal-pulling furnace.

crystal and another thin layer of molten silicon is formed. The process eventually results in a single crystal silicon bar.

A variety of tests are made on single crystal germanium and silicon to determine the dopant concentration and other properties of a particular ingot. The most routine measurement is resistivity. Ordinary ohmmeters are not used. Instead, special multicontact meters which apply tiny amounts of current to the sample under test are employed. By using very small, closely-spaced contacts it's possible to accurately measure the resistivity of an ingot along its entire length without altering its properties. Measurements are not necessarily made on all ingots but may be used to spot-check the quality of a number of crystals grown from a single batch of purified semiconductor.

JUNCTION FORMATION

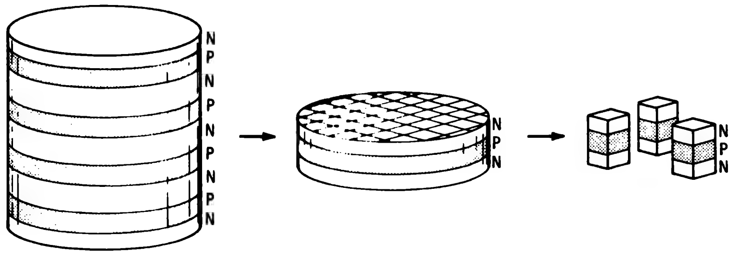
A fascinating variety of techniques has been developed to form the two pn junctions necessary for transistor action to occur. The most common ones are: grown junction, alloy junction, diffused junction, and epitaxial junction. From these various junction-formation techniques dozens of different transistor structures have evolved. We will describe several of the important ones, but first let's discuss the grown junction.

Grown Junction

This is the earliest technique used to make junction transistors. Grown junctions are formed by changing the impurity concentration as a germanium crystal is being pulled from the melt. The process is simple. First, the melt is doped with a donor to obtain n-type material. After the crystal has been pulled slightly from the melt, enough acceptor dopant is added to counteract the original donor dopant and a thin layer of p-material is grown. The process is repeated again to give another layer of n-material. As shown in Fig. 3-4, the end result is a crystal with consecutive npn layers. By reversing the doping procedure, pnp layers can be formed also.

After a bar of junction crystal is grown, it is sliced by a diamond saw into wafers containing two junctions (pnp or npn). To facilitate the attachment of connecting leads, the wafers are usually lapped to make their saw-roughened surfaces smoother. Then each wafer is scribed along crystalline planes and broken into individual transistor chips. One wafer may yield several hundred transistors.

An advantage of the grown junction technique is that several npn or pnp sandwiches can be grown at one time in a single



(*A*) *Crystal.* (*B*) *Wafer.* (*C*) *Transistor chips.*

Fig. 3-4. Grown junction transistor formation.

crystal. To accomplish this kind of growth a *rate-grown* method is employed. The technique is quite similar to the standard grown junction method except both acceptor and donor dopants are initially added to the melt. The crystal is then pulled from the melt at varying rates. Since p- and n-dopants tend to concentrate at different rates, pnp or npn sandwiches are formed.

Alloy Junction

Another early method of making transistor junctions is alloying. In this method two small dots of indium, a soft, silvery-white metal, are placed above and below a chip of n-type germanium. One of the indium dots is slightly larger than the other. The combination is held in place inside a graphite jig and heated to the melting point of the indium. When the indium begins to melt, some of it combines with the adjacent germanium. Since indium is an acceptor dopant, thin regions of p-type germanium are formed directly next to the indium pellets. The assembly is then cooled and is ready for attachment of emitter, collector, and base wires. The central n-region becomes the base, while the large indium dot becomes the collector and the small one the emitter. The manufacturing process is summed up in Fig. 3-5 and a cross section of a complete alloy transistor is shown in Fig. 3-6.

The advantage of this particular technique is that the finished transistors are merely a few steps away from completion. Alloy-junction transistors are relatively easy to manufacture and are low in cost. Their frequency response, however, is limited to about 20 MHz due to the rather thick base region. Better frequency response is obtained by using a unique *micro-alloy* technique to form a transistor with a thin base region. In this method, two jets of liquid electrolyte are directed against the flat base material in order to etch away two pits opposite one another. When the jets have etched away the

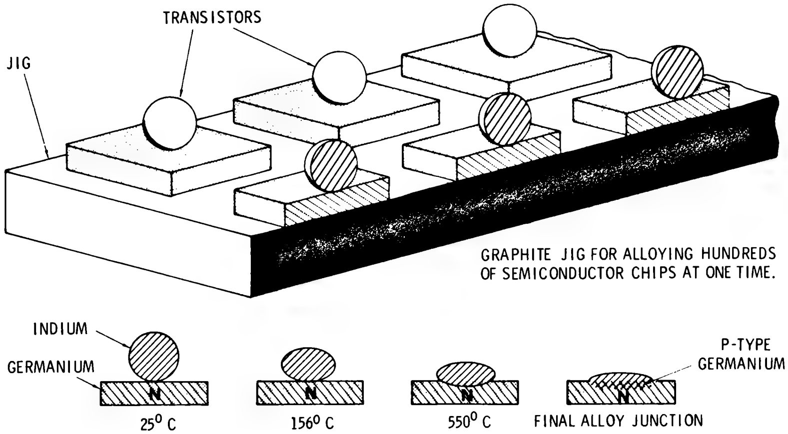


Fig. 3-5. Manufacture of alloy junction transistors.

proper amount of material, the pits are electroplated to form junctions and contact points. Transistors made in this manner have excellent frequency response but are structurally fragile.

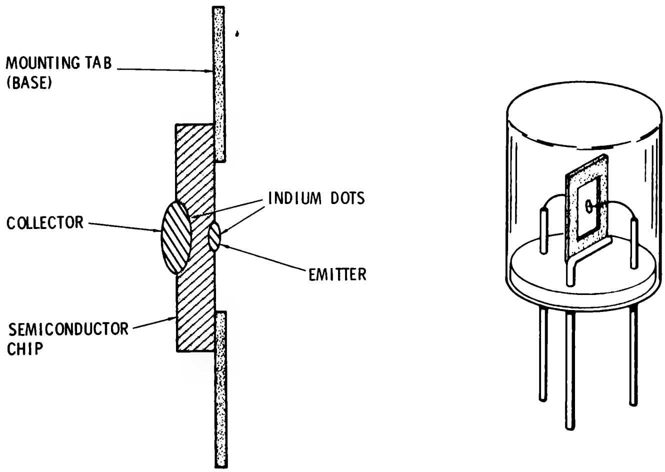


Fig. 3-6. Cross section of a complete alloy junction transistor.

Diffused Junction

Very predictable transistor junctions can be obtained by diffusion. In this process, as shown in Fig. 3-7, the semiconductor wafer is placed in a closed furnace and heated in the presence of a dopant. When the temperature conditions are right, the dopant will evaporate and its atoms will diffuse through the exposed portions of the wafer. Since the penetration rate of

various dopants is well known, it is possible to accurately control the placement of the resulting junction.

By diffusing both sides of an n-wafer with an acceptor dopant, a pnp sandwich is formed. The npn structures are formed similarly. It is relatively common to use diffusion techniques to form one of the transistor junctions and another method for the remaining junction.

As we shall soon see, diffused transistors are in wide use. While certain kinds are difficult to manufacture and involve numerous fabrication steps (with possibly two or three separate diffusions), large numbers can be made at one time by using a photoresist process similar to that used in manufacturing printed-circuit boards.

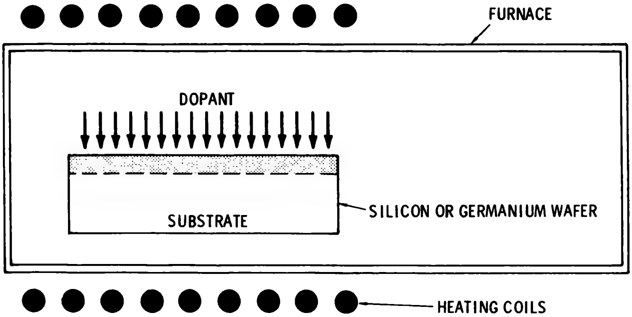


Fig. 3-7. Diffusion process.

Epitaxial Junction

While not as frequently employed, the epitaxial process produces very uniform pn junctions. Typically, a wafer is heated in the presence of a gas which will react with the wafer to form a thin layer of identical semiconductor but with opposite polarity. The process is called vapor phase epitaxy and is summarized in Fig. 3-8.

A related kind of junction formation is liquid phase epitaxy. Here the wafer is wetted with a molten semiconductor of opposite polarity. When the wafer is removed from the melt, the thin coating of semiconductor "freezes" on its surface to form a very thin, uniform junction.

While the eiptaxial process is not often used in making transistor junctions, the resistivity characteristics of an epitaxial layer have been extensively used in fabricating certain kinds of transistors. Practically all planar transistors are made in epitaxial layers, and we will describe how this is done shortly.

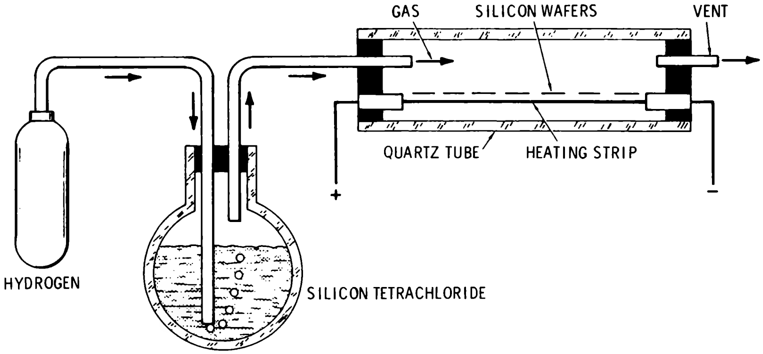


Fig. 3-8. Vapor phase epitaxy.

TRANSISTOR STRUCTURES

The previous section on junction formation has provided several clues on how working transistors can be made, and in this section we will describe several of the most commonly used methods. Keep in mind that space limits us from going into all the details about how the structures are formed—we have to go on to the transistors themselves in a few pages. However, the highlights are here, and they should provide a good basis for understanding the numerous variations which exist.

Alloy Transistors

Much of the process for making alloy transistors was described in the section on alloy junction formation. After the required junctions are formed on either side of tiny silicon or germanium chips, each individual chip is attached to a *header* by welding the metal base tab to one of the header's three leads. (The leads are insulated from the header by glass sleeves.) Next, very thin leads are welded to the indium dots forming the collector and emitter and to the remaining leads emerging from the header.

Before the transistor and header are installed in a protective can or cover, the entire unit is carefully etched and washed to remove any foreign matter which might short circuit the junctions. Then a metal can is placed over the header and welded in place. More details on how transistors are enclosed in metal and plastic packages will be provided later in this chapter.

Mesa Transistors

More rugged than the alloy and grown junction structure, the mesa transistor is formed using photoresist and etching

techniques. Though there are several variations, a mesa transistor is often formed by diffusing an acceptor dopant into an n-wafer to give a base-collector junction. The collector, which forms the substrate for the transistor, may by 25-thousandths of an inch square.

Next the top surface of the chip, the base, is oxidized by a photoresist process which leaves a tiny opening near the center of the chip. The dimensions of the chip can be carefully controlled since a photographic process is used to reduce a much larger original pattern down to a few thousandths of an inch across. A second diffusion step then forms an emitter section into the transistor structure.

The final semiconductor treatment gives the mesa transistor its name. To isolate the base-collector junction and reduce its overall area, an etching process is used to remove the excess substrate (collector) material from around the central junction region of the device. Since this leaves an area projecting from the substrate, *mesa,* the spanish word for table or platform, is used to describe the transistor.

The deposition of aluminum contacts over the base and emitter regions completes the semiconductor processing steps, and the chips are then ready for packaging as individual transistors. The resulting structure is shown in Fig. 3-9.

The mesa transistor has a variety of useful properties. Frequency response and power capability are good and the completed device is more rugged than alloy types. However, the exposed junction edges of the mesa structure are extremely vulnerable to shorting caused by contaminants. To alleviate this problem and still preserve the excellent properties of the mesa structure, the *planar* transistor was invented.

Planar Transistors

The manufacture of a planar transistor is a complicated but marvelous process. By precision photoetching techniques, the

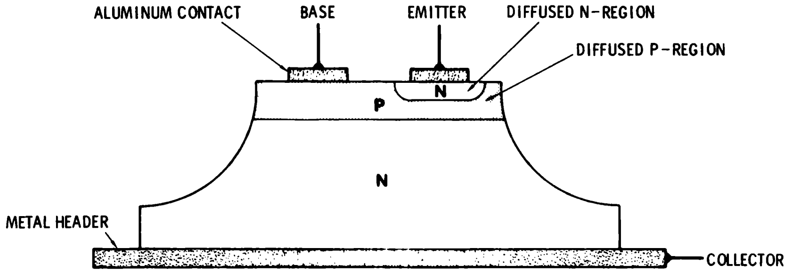


Fig. 3-9. Mesa transistor construction.

entire transistor is literally buried within a layer of silicon or germanium. Here's how it is done.

To make a silicon npn planar transistor, an n-type silicon wafer is coated on one side with a thin layer of glasslike silicon oxide. The coating is relatively easy to obtain since silicon oxide is produced when very hot silicon is exposed to oxygen. Next a photoresist is sprayed onto the silicon-oxide layer and a photographic mask is used to expose a circular opening on the resist. This is one of the wonders of the planar structure. Since photographic procedures are used to outline the various parts of each transistor, literally hundreds of transistors can be made on a single silicon wafer at the same time.

When the photoresist is developed, a circular opening corresponding to the photographic mask is removed. This permits the silicon-oxide layer directly under the opening to be etched away without affecting the remaining silicon oxide, since the photoresist is not attacked by the etching chemical.

After the circular area of silicon oxide is removed, the exposed n-type silicon is diffused with an acceptor dopant to give a base-collector pn junction.

By applying a second coating of photoresist and forming a smaller circular opening inside the first, a second pn junction is formed. This gives the complete npn transistor. Metal contacts are evaporated onto the appropriate sections of the transistor, and the exposed base-emitter junction is oxidized to give a silicon-oxide coating. The process is summarized in Fig. 3-10.

Since all the junctions of the planar transistor are either buried within the silicon substrate or coated with silicon oxide, there is little chance contamination will affect the device. This high degree of reliability coupled with ruggedness and good frequency response, make the planar transistor popular for many applications.

PACKAGING

All transistors are relatively fragile, since tiny wires are usually used to make contact with at least one of the base, emitter, or collector sections. Also, both silicon and germanium are very brittle crystals. To protect the chip and its connections from mechanical damage, nearly all commercial transistors are sealed in metal cans or potted in sturdy plastics.

The cross section of a typical metal-encased transistor is shown in Fig. 3-11. Often inert fluids or silicone greases are placed in the can before it is welded to the header to provide a second defense against water vapor or other contaminants.

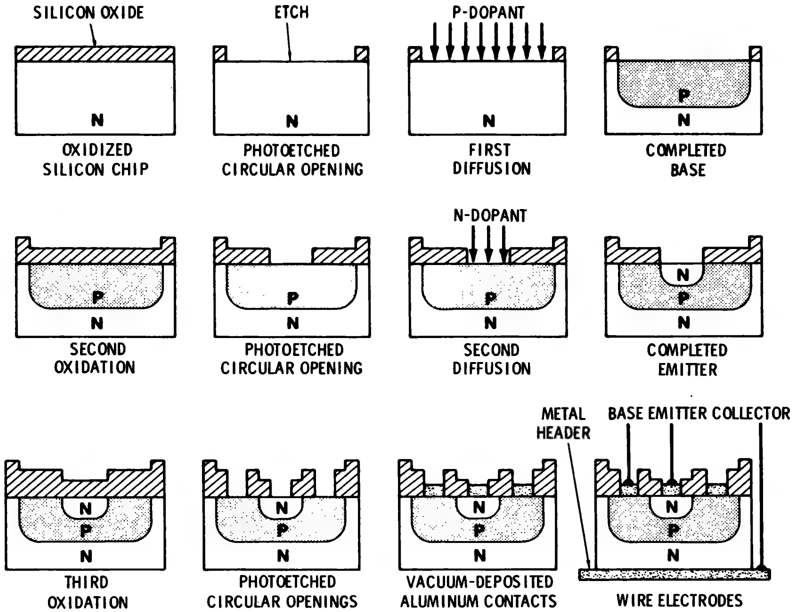


Fig. 3-10. Planar transistor fabrication.

This is good protection since bending the transistor's external leads may open tiny channels into the sealed can.

Though metal encased transistors are extremely sturdy, the costs of packaging add significantly to final pricing of commercial units. Therefore, most companies also encase their transistors in plastic. While plastic transistors are much cheaper than metal encased units, many companies were at

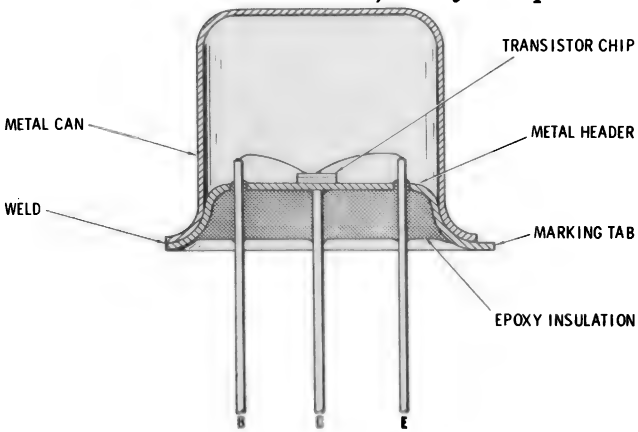


Fig. 3-11. Cross section of a metal-encased transistor.

first reluctant to use them. The military was particularly wary and even now limits their use to certain noncritical applications.

The reason for the doubt is that some very bad experiences were had with early plastic encased transistors. One problem was that light tended to travel through the partially transparent plastic and affect the transistor's operation. That problem was solved by developing highly opaque plastics and was a minor irritant compared to the major problems of contamination from water vapor and other material. Also, plastic transistors are just not as sturdy as metal encased units.

A concentrated research effort has finally eliminated most problems associated with plastic encased transistors. Though certain critical military and industrial applications still require their metal encased cousins, plastic transistors are finally finding very wide acceptance in all sorts of applications.

Besides being inexpensive by virtue of not having to undergo hermetic sealing inside a metal can, plastic transistors offer another important advantage. They can be manufactured automatically in huge quantities by special machines. Some semiconductor companies have been using such machines for more than six years now and an important result is very inexpensive transistors. In 1960, good transistors cost several dollars each, but today the experimenter can buy half a dozen plastic transistors with even better capabilities for the same amount of money.

CHAPTER 4

TYPES OF TRANSISTORS

The various junction-forming and manufacturing techniques described in Chapter 3 can be combined to give numerous different kinds of transistors. The reason no one particular manufacturing method is used over the others is that frequency response, switching speed, gain, and other factors can be better controlled by selecting particular kinds of fabrication.

In this chapter we will first discuss the transistors made from the processes already described. Then we will get into the specialized transistors that are being used more frequently in modern circuit design. Finally, the chapter will conclude with a discussion of some very unique, special-purpose transistors.

GERMANIUM VERSUS SILICON

We have already noted that both germanium and silicon have relative advantages and disadvantages when used in transistors. The relative merits of each material are very important to transistor design.

First, recall that germanium has a much lower resistance than silicon. This characteristic is important in applications where current losses in a transistor cannot be tolerated. A good example of where a germanium transistor proved superior to silicon units is in a pulse generator designed to operate a light-emitting diode in a miniature optical radar. The current pulses through the LED have to be as high as possible in order to obtain the maximum amount of infrared output, and only germanium transistors had an "on" resistance low enough to give the desired current.

Another advantage of germanium over silicon is ease of purification. With its relatively low melting point, germanium is much easier to purify than silicon. One of the major disadvantages of germanium transistors is the tendency toward *thermal runaway.* As the name implies, this conditions occurs when the transistor is permitted to become too warm. Since the resistance of germanium decreases as temperature increases, the transistor permits more current to flow as it warms up. Sometimes the cycle perpetuates itself until the transistor is destroyed. Silicon transistors are not immune to the phenomenon of thermal runaway, but their better temperature capability makes them less susceptible than germanium devices.

Thermal runaway can be controlled by careful biasing techniques or use of temperature-sensing resistors called thermistors. In the latter case, a thermistor is sometimes attached to the transistor's case and used to control the amount of bias in the transistor. As the transistor warms up, the thermistor's resistance changes and the current through the transistor is reduced.

Silicon transistors have far better temperature immunity than germanium units. Additionally, silicon is far more common than germanium since it accounts for about 85% of the earth's crust. Ordinary beach sand is composed primarily of silicon. Germanium, on the other hand, is relatively rare. It is found in certain copper and zinc ores and is almost always a byproduct of zinc refineries. Good yields may produce up to half a pound of germanium for every ton of processed ore.

Initially, silicon transistors were far more expensive than their germanium counterparts, but the technology of purifying the element has improved to the point that costs are now very competitive. High quality silicon and germanium transistors are now available for less than 50¢ each in single unit quantities, and for only pennies each in volume or as surplus.

Though silicon and germanium are the most common transistor materials, it should be noted that several other semiconductors have been employed in experimental transistors. A major goal of using different semiconductors is to achieve much higher frequency responses than are possible with silicon and germanium. Transistors made from gallium arsenide, for example, will operate well into microwave frequencies with high efficiency. Gallium arsenide has a high radiation resistance and has therefore been investigated for some time as a suitable semiconductor for spaceflight applications. Though only specialized transistors are now made from the material, research with gallium arsenide has led to very efficient semi-

conductor injection lasers, light-emitting diodes, and microwave generators.

Gallium arenside is an *intermetallic* or *three-five* compound. While silicon and germanium have four valence electrons, gallium arsenide is a combination of an element with three valence electrons (gallium) and an element having five valence electrons (arsenic).

Other intermetallic compounds suitable for use in semiconductor applications include gallium phosphide, indium arsenide, gallium arsenide phosphide, indium antimonide, and indium phosphide. While some of these compounds are very difficult to fabricate into working semiconductor devices, several are being used in light-emitting diodes and magnetic-sensitive components. As processing techniques improve, more of these intermetallic semiconductors will be used in solid-state devices.

BIPOLAR JUNCTION TRANSISTORS

Since the transistors we have discussed so far have two types of semiconductor material, positive (p) and negative (n), they are called *bipolar* devices. Bipolar transistors are the ones most commonly used and literally thousands of different types are available.

We have already described how they are made, so now it's appropriate to list some of the characteristics of bipolar transistors.

Alloy Junction

Typical alloy junction transistors are the Radio Shack types RS-2001 through RS-2007. These particular transistors are made of germanium. Since germanium has a lower resistance than silicon, they are useful in switching applications requiring a low voltage drop across the transistor. While the power dissipation of these devices is not as high as silicon transistors, they all have relatively high gain.

Most alloy junction transistors have limited frequency response and are therefore better suited to audio applications. The RS-2003, however, is manufactured with a partially diffused germanium chip so that the impurity concentration near the base-emitter junction is much higher than that near the base-collector junction. Two important advantages result from this kind of structure. First, the graded impurity concentration in the base region tends to speed up current flow, and second, the structure tends to reduce capacitive effects between the junctions of the transistor. The end result is an alloy tran-

sistor with much higher frequency response than conventional alloy units.

Alloy transistors made in this fashion are called "drift field" or just "drift" transistors after the tendency for electrons to drift toward the more positive section of the base and holes to drift toward the more negative sections. The RS-2003 has an upper frequency response of about 50 MHz and is therefore well suited to radio-frequency applications.

Diffused Mesa

As noted in Chapter 3, the application of diffusion techniques greatly simplified the manufacture of transistors with predictable, repeatable characteristics. In addition to improving the yield of a particular kind of transistor, mesa construction gives units a much higher frequency response and current capability than alloy transistors.

The Radio Shack RS-2017 through RS-2020 are examples of mesa transistors. All four of these units are npn silicon power transistors capable of handling from 30 to 90 watts. They are mounted in tab cases and can be used as high speed switches or power amplifiers.

The complements to three of the previous transistors are also available. Designated RS-2025 through RS-2027, these mesa transistors have the same characteristics as their npn counterparts.

Diffused Planar

The planar technique is probably used to make more transistors than any other manufacturing process. As explained in Chapter 3, planar technology preserves the advantages of mesa construction while sealing all exposed junctions in a protective coating of silicon oxide.

Radio Shack offers more than fourteen different planar transistors. For more careful control of final characteristics, most of these transistors are formed in an epitaxial layer grown over a low-resistance silicon substrate.

The flexibility of silicon epitaxial planar transistors is broad indeed. They can dissipate almost twice the power of similarly packaged germanium alloy types without special heat sinking. Due to very thin base regions (a result of careful diffusion timing), the frequency response is good. Typical planar transistors such as the Radio Shack types RS-2009 and RS-2015 perform well at frequencies in excess of 100 MHz.

Radio Shack planar transistors are available in both metal and plastic packaging. Because of the development of a new

plastic compound which is both sturdy and impervious to light, the plastic versions can be used in practically any application. The cases are so sturdy they can withstand soldering temperatures without being deformed.

FIELD-EFFECT TRANSISTORS

Closely related to semiconductor devices first proposed in 1925 by J. E. Lilienfeld, the modern field-effect transistor (FET) offers several important characteristics not available with conventional bipolar devices. The best characteristics of the FET are a very high input impedance, good frequency response, and low noise.

FETs are made in a number of configurations and we will describe several of them here. The first to be developed was the junction FET (JFET). This transistor consists of a single bar of either n- or p-type semiconductor with a contact affixed to each end (Fig. 4-1). The bar is called the channel since it serves as a current path, and the terms n-channel or p-channel are used to designate the primary current carrier in the bar.

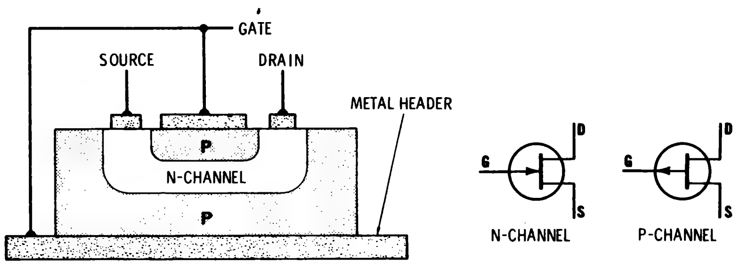


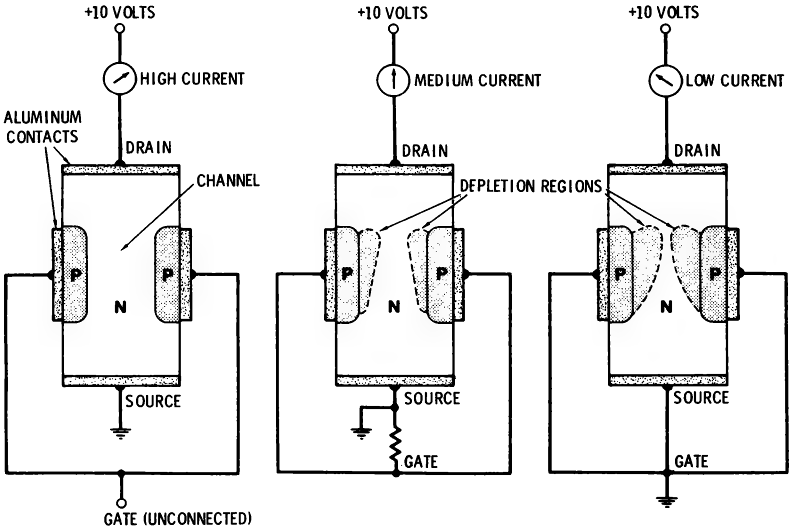
Fig. 4-1. An n-channel JFET.

One of the two leads is designed to be connected to a source of current and is called the *source* electrode. The other lead is called the *drain*. A third connection surrounds all or part of the channel region between the source and drain connections and is called the *gate*.

The operation of the FET is very similar to that of a triode electron tube. Current flows through the channel from source to drain very much like electrons in a tube flow from cathode to plate. When a small voltage with the same polarity of the channel material is placed on the gate electrode a field is built up which tends to restrict the free flow of channel current. As the gate voltage is increased, a point is reached where the field extends completely across the channel and the current flow is

completely blocked. This cutoff point is often referred to as "pinch-off" and is shown in Fig. 4-2.

Like the electron tube, only a tiny amount of current flows in the gate (grid) circuit. This is because there is an extremely high resistance between the gate and both source and drain electrodes. The channel resistance itself (source to drain) is usually no more than a few thousand ohms.



(*A*) *Zero gate bias.* (*B*) *Low gate bias.* (*C*) *High gate bias.*

Fig. 4-2. Operation of an n-channel JFET.

The very high gate channel resistance of the junction FET, on the order of a few million ohms, provides the high input impedance required in a wide variety of electronic circuits. Formerly, bipolar transistors were so limited in high impedance circuits that additional components were needed, and in some cases designers were forced to stick with the bothersome electron tube just to obtain the required input impedance.

More recently new kinds of FETs with gate-channel resistances of thousands of megohms have been developed. These new FETs are made possible by the fact that the gate is used to establish a field in the channel region. Since direct contact is not required to establish the channel-voltage field, a thin layer of silicon oxide is formed over the channel, as shown in Fig. 4-3, to insulate the gate from the semiconductor forming the channel. It is the glasslike silicon oxide which gives the gate-channel resistance thousands of megohms.

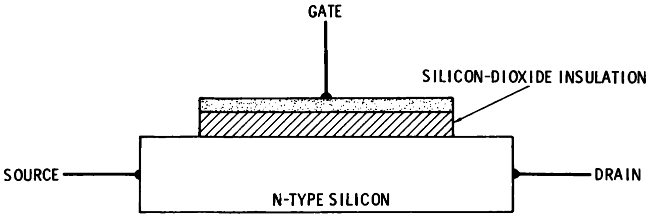


Fig. 4-3. Insulating the gate from the channel.

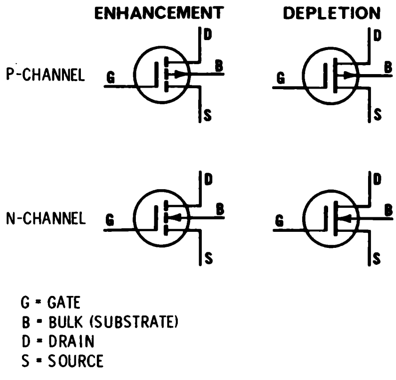
Depending on the manufacturer, FETs made with an insulated gate are called IGFETs (insulated gate FETs) and MOSFETs (metal-oxide-semiconductor FETs). Both IGFETs and MOSFETs are made in half a dozen different configurations in order to obtain special characteristics.

As with the JFET, both IGFETs and MOSFETs are made with p- and n-channels. These categories are further subdivided into three additional configurations: enhancement, depletion, and enhancement/depletion. There are also IGFETs and MOSFETs with two separate gates. These dual-gate FETs also have, in effect, two channels. The circuit diagram symbols for some of these FETs are shown in Fig. 4-4.

The JFETs we described earlier were characterized as presenting little resistance to the flow of channel current until gate voltage was applied. Enhancement IGFETs and MOSFETs, on the other hand, act like conventional bipolar transistors in that channel current does *not* flow until gate voltage is present. The big advantage of the FET, of course, is that it retains a very high input impedance.

The way enhancement IGFETs and MOSFETs achieve this capability is by separating the source from the drain and plac-

Fig. 4-4. The IGFET (MOSFET) symbols.



ing the insulated gate over both. Normally, no current can flow through the interrupted channel, but application of gate voltage turns the transistor's channel "on." This normally "off" FET is well suited to switching applications.

Depletion IGFETs and MOSFETs are similar to standard FETs since the channel region is continuous. A fourth electrode connected to the channel region permits more control over the operation of the transistor. The resultant structure is shown in Fig. 4-5.

A type of depletion FET which shows some channel current flow when no gate voltage is present is sometimes called the enhancement/depletion FET. Since the current can be cut back to zero by application of negative gate voltage or increased over the zero gate voltage value by applying a positive gate voltage, enhancement/depletion FETs are valuable for use in both voltage and rf amplifier circuits.

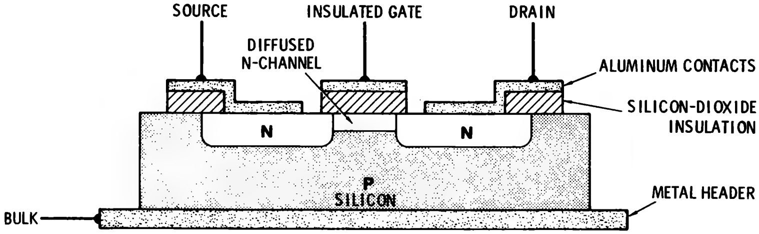


Fig. 4-5. Basic structure of a depletion IGFET (MOSFET).

While field-effect transistors have several highly desirable characteristics, they haven't yet found the wide range of applications presently served by bipolar devices. An important disadvantage is that insulated-gate FETs are susceptible to damage from static electricity. This is because the layer of glasslike silicon oxide is very thin and is easily penetrated by static discharges. Since rubbing a transistor's leads on ordinary plastic can generate a static discharge of several thousand volts or more, IGFETs and MOSFETs are almost always shipped in electrically conducting containers with their leads twisted together. The leads should not be untwisted until the transistor is soldered into a circuit and even then a small strip of aluminum foil should be wrapped around the leads just below the transistor and removed only after soldering is completed.

Though individual FETs are not yet used on as wide a scale as bipolar transistors, MOSFET technology has made important contributions to integrated circuitry. FET structures are less complex than their bipolar counterparts, therefore, far

more FETs can be fabricated onto a silicon chip. MOSFET integrated circuits have been assembled which have the equivalent of more than 150,000 components per square inch.

Unijunction Transistors

Though its properties are unlike those of any transistors discussed so far, the unijunction transistor (UJT) is a very useful device. Referring to Fig. 4-6, note that the internal structure of the UJT is very similar to that of the junction FET. In the configuration shown there, called the bar structure, a small bar of n-type silicon is attached to a thin ceramic disc. Contacts are made directly to each end of the bar on either side of the disc and a pn junction is formed near one end of the bar by alloying a thin aluminum lead to the top surface of the bar. The disc is attached to a header and the entire assembly is enclosed in a plastic or metal case.

Another kind of UJT is made with a cube of n-type silicon. This kind of UJT has certain characteristics which make it more suited to low-voltage operation. The bar structure, however, performs better at temperature extremes.

The major application for the UJT is in pulse and waveform generation circuits. Such circuits are commonly used to switch SCRs on. In a typical UJT oscillator, such as the one shown in Fig. 4-7, a capacitor (C1) is charged through resistor (R1) until the capacitor voltage reaches the value of the voltage between B1 and the n-side of the emitter's junction. Until this point is reached, the "diode" formed by the emitter-B1 junction is reverse biased and does not conduct. But when the proper

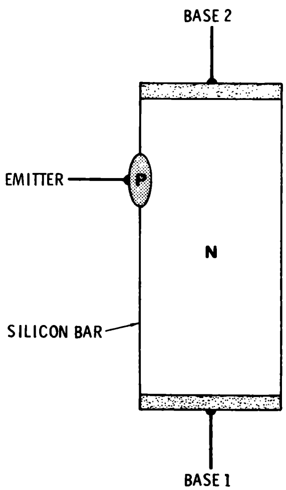


Fig. 4-6. Simplified unijunction transistor.

voltage is reached the emitter-B1 junction becomes forward biased and immediately switches on. The capacitor is then shorted across R3 and discharged in a very rapid pulse. The pulse can be seen by connecting an oscilloscope from B1 to ground.

When the capacitor is discharged, the emitter-B1 junction is again reverse biased and C1 begins charging again. The charge-discharge cycle repeats itself at a rate which can be varied by appropriate adjustments of R1 and C1.

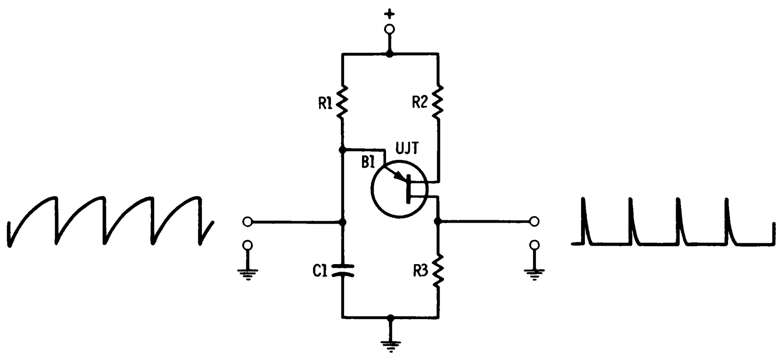


Fig. 4-7. Unijunction oscillator.

In addition to producing a series of brief spikes, the unijunction oscillator shown in Fig. 4-7 also produces a modified triangle wave or "ramp." The ramp can be seen by connecting an oscilloscope across the capacitor.

POWER TRANSISTORS

Actually, power transistors are almost always bipolar junction transistors. But their mechanical structure and applications are so different they deserve a section of their own.

Because the small chips of semiconductor material used to make transistors possess some resistance to the flow of electrons, they tend to warm up as the current flow is increased. Germanium transistors, as we have already noted, can be seriously damaged by the thermal runaway which eventually accompanies excessive heating. While silicon can withstand much higher operating temperatures than germanium, the high power requirements of many amplifier, converter, inverter, and other power circuits require current levels which would quickly ruin even silicon transistors.

Sometimes transistors are cooled by fans or miniature refrigeration systems. But this is often impractical, particularly where the transistors are being used in consumer and experimenter electronics.

The solution to the problem is to use a massive metal case for the transistor which is in intimate contact with one of its three regions, often the collector. The metal acts like a heat sink and serves to radiate heat generated in the transistor junction into the surrounding air by means of convection.

Sometimes additional heat sinks with heat-radiating fins are used in conjunction with power transistors. Capacitive discharge systems for automobiles, hi-fi amplifiers, and power supplies are common examples where this additional heat sinking is employed.

Besides metal heat sinks, power transistors usually employ specially modified junctions which permit more of the internally generated heat to be radiated to the heat sink. Since mesa and planar structures have a relatively large amount of chip area in direct contact with the metal transistor header, they are often used in power transistors.

Other than their special mechanical configurations, operation of bipolar power transistors differs little from that of standard units. The major difference is, of course, that the power transistor can be operated at power levels of up to 100 watts or more.

Radio Shack offers several quality power transistors employing a metal tab heat sink. This kind of heat sink has become more popular than large metal cases since it gives a much more compact transistor package.

SPECIAL PURPOSE TRANSISTORS

Some of the standard bipolar and unipolar (FET) transistors are well suited to specialized applications. Some applications such as detecting light, are relatively common. Others, however, can be very unusual. Several of these special purpose transistors are described below.

Phototransistors

Early in the development of practical transistors it was noticed that semiconductor junctions became more conductive when exposed to light. By intentionally leaving an opening in the case, transistors can be made to respond to light and perform useful work. These modified transistors are usually called *phototransistors*.

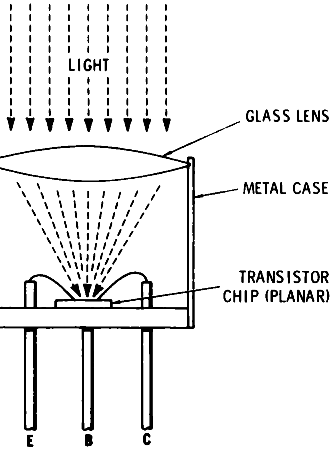


Fig. 4-8. Cross section of a phototransistor.

Practically any transistor will respond to light in one way or another and several years ago it wasn't uncommon for an engineer to simply saw the end from the case of a standard transistor to obtain a makeshift, but working, phototransistor.

Now, however, literally dozens of kinds of phototransistors are manufactured by many semiconductor companies. A typical such transistor is shown in the cross section in Fig. 4-8. This particular transistor has a small glass lens to focus light onto the semiconductor chip, but others are available with flat glass windows so external lenses can be used. A unique feature of the plastic encased units is that the lens is formed from the case itself.

An interesting feature about phototransistors is that the base lead, if present, is not necessarily used. The light striking the base region serves as a stimulus to transistor action and is identical in effect as if electrical bias current had been applied to the base.

Ultrahigh-Frequency Transistors

Considerable progress has been made in applying transistors to uhf and microwave applications. These transistors are often enclosed in special containers, with access provided to the various semiconductor sections with strips of metal rather than ordinary wires. Since operation at frequencies of 100 MHz or more often causes oscillation and impairs gain, transistors designed to be operated at such frequencies are mounted using a stripline technique instead of conventional wiring. The metal striplines present very little resistance and inductance, and therefore enhance operation at high frequencies.

Pressure-Sensitive Transistors

In 1962, Dr. W. Rindner, then employed by the Raytheon Corporation, noticed that current fluctuations occurred when a sharp probe was pressed against a germanium diode. He concluded a study of this effect and found that pressures of a small fraction of an ounce would change the current by several decades.

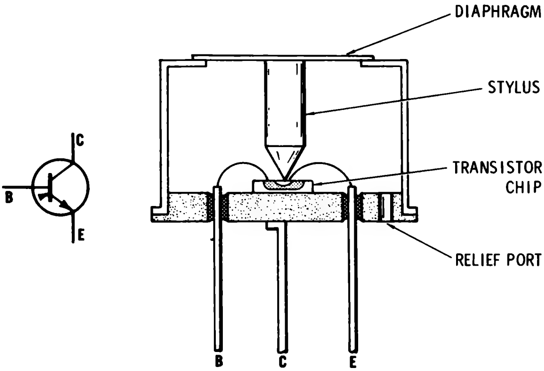


Fig. 4-9. Internal construction of a PITRAN.

Scientists in several countries studied the pressure sensitivity of semiconductor junctions, and in 1966, a company, called Stow Laboratories, was formed to manufacture commercial pressure-sensitive transistors. The company now markets a line of these unique devices, called PITRAN, for use in sensitive scales, leak detectors, accelerometers, air speed detectors, and high-intensity blast gauges.

The internal construction of a PITRAN is shown in Fig. 4-9. The stylus is attached to a flexible diaphragm and normally rests on the surface of a planar transistor chip. When the diaphragm is forced inward by pressure, the stylus presses against the transistor chip and causes an increase in output current directly proportional to the amount of pressure.

CHAPTER 5

HOW TO USE TRANSISTORS

This book includes a number of transistor circuits which the experimenter can easily assemble and operate. So that the operation of these circuits can be better understood this chapter is intended to explain some of the practical aspects of using transistors. We will get into some transistor principles shortly, but first let's review some basic electronics in order to be better prepared for discussing transistor operation.

BASIC ELECTRONICS REVIEW

Transistor circuits almost always use a variety of electronic components for proper operation. While components which amplify an electronic signal (e.g. electron tubes and transistors) are called *active* components, those which assist in the amplification process are called *passive* components.

Three classes of passive components are very important in most transistor circuit applications: resistors, capacitors, and inductors. There are other passive components as well, but these are the ones most frequently employed in transistor circuits.

Resistors

As the name implies, resistors resist the flow of an electrical current. Above the temperature of absolute zero even the best conductor presents some resistance to a current. For many applications, fairly high resistances are needed. And to obtain them, specially formulated carbon mixtures or high resistance wires are molded in thin plastic or ceramic tubes with a wire emerging from each end. The tube is usually coded with the amount of resistance by a series of colored bands (Fig. 5-1).

The unit of resistance is the *ohm,* and the current is directly related to the value of the resistor and the voltage across it. This relationship is dependent on the fact that voltage divided by resistance equals current.

Resistors come in values ranging from less than a tenth of an ohm to hundreds of megohms (a megohm being one million ohms). They are also available in a variety of wattage ratings. High-wattage resistors are used in high-power applications where the resistor will be required to dissipate heat. Potentiometers, rheostats, and trimmers are adjustable resistors.

COLOR	FIRST BAND	SECOND BAND	THIRD BAND (MULTIPLIER)
BLACK	0	0	1
BROWN	1	1	10
RED	2	2	100
ORANGE	3	3	1000
YELLOW	4	4	10,000
GREEN	5	5	100,000
BLUE	6	6	1,000,000
VIOLET	7	7	10,000,000
GRAY	8	8	100,000,000
WHITE	9	9	

Fig. 5-1. Resistor color code.

Capacitors

These devices come in dozens of sizes and configurations but, in theory at least, always consist of two plates of conducting material separated by an insulator called a dielectric.

Capacitors have several unique properties which qualify them for use in transistor circuits. Their best known capability is storing an electric charge; hence they are rated in terms of their maximum storage ability. The unit of capacitance is the *farad,* but transistor circuits almost always use capacitors rated in microfarads (μF) or picofarads (pF).

Since capacitors can store an electric charge, it's not uncommon to connect a large value capacitor across the battery terminals of some transistor circuits. If the circuit suddenly requires a momentary increase in current, the capacitor acts

like a battery in parallel with the power-supply battery and helps to supply the demand.

Capacitors are often used to filter pulsating electrical currents for operation of transistor circuits. This is particularly true when the circuit is operated from household ac. But though an ac current is filtered or smoothed out when a capacitor is connected across it (parallel), it is not affected when the capacitor is connected in series with it. This interesting property is very useful in transistor circuits. By placing series capacitors before each transistor in an amplifier, for example, each transistor is isolated from its neighbor. The ac signal gets through without any trouble, but dc is completely blocked. Capacitors used for this purpose are called *blocking* capacitors.

Inductors

In its simplest form an inductor is merely a length of wire formed into a coil. An inductor has no effect on a direct current, but it can be used to control an alternating current.

Inductors may be in the form of coils which are operated in parallel with a capacitor to achieve a frequency resonance. By properly tuning the coil (usually by moving a ferrite slug through a hollow corte) or adjusting the capacitor, the circuit will resonate at a single frequency and be very useful in selecting frequencies in a radio receiver.

Inductors are also used to smooth out an alternating current. Their resistance to dc is very low but their ac resistance (impedance) is very high.

Transformers represent still another kind of inductor. Because of their impedance conversion ability, transformers are ideal for matching separate sections of a transistor circuit.

The unit of inductance is the *henry*. One henry is the inductance present in a closed circuit when an alternating current variation which varies its rate of flow by one ampere per second induces a force of one volt. Several common inductors are shown in Fig. 5-2.

Impedance

Impedance is a term frequently encountered in transistor circuit description. The word refers to the opposition a circuit presents to an ac signal and is measured in ohms.

Impedance is designated by the letter Z and is derived by combining a circuit's reactance and resistance.

The input impedance of a circuit is very important since whatever device is to be connected to the circuit must have a similar impedance. If the input impedance of a transistor am-

plifier is, for example, 2500 ohms, there would be little use in connecting a high-impedance crystal microphone to the circuit since little or no signal generated by the microphone would be transferred into the amplifier.

Similarly, there would be little efficiency in connecting a low-impedance (e.g. 8 ohm) speaker to a transistor amplifier with an output impedance of 800 ohms. As with the crystal microphone, very little signal would be coupled from the amplifier to the speaker.

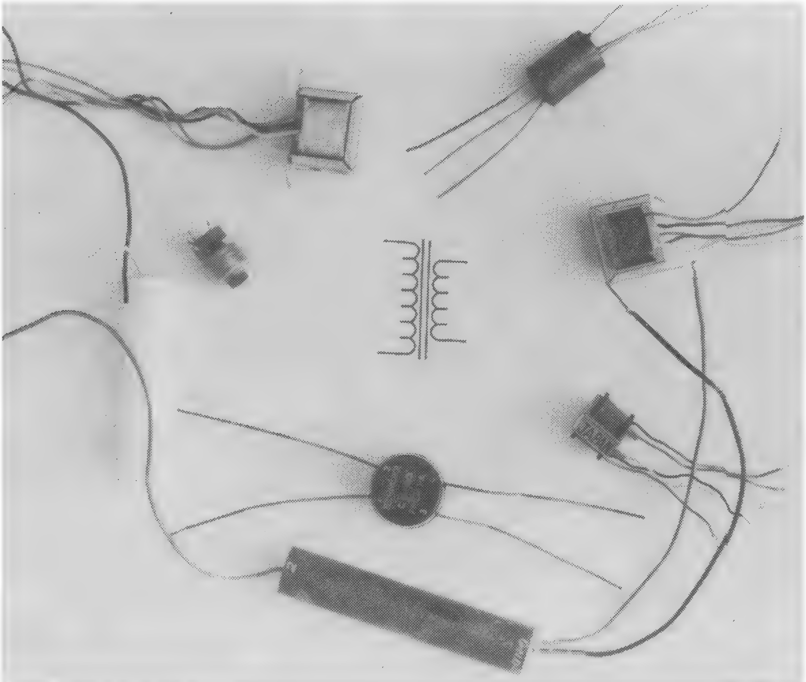


Fig. 5-2. Typical inductors.

Several techniques are used to match impedances in transistor circuits. One of the most efficient methods is the use of an interstage transformer. By selecting a transformer whose primary impedance matches that of one stage of an amplifier and whose secondary impedance matches that of the next stage, a near perfect impedance match can be obtained.

Transformers can also be used at both input and output stages of transistor circuits. In the case of the amplifier and speaker mentioned previously, a transformer whose primary winding has an impedance of 800 ohms and whose secondary

has an impedance of 8 ohms would efficiently couple the amplifier to the speaker.

Transformers are very efficient impedance-matching devices, but they are relatively large, bulky, and heavy when compared to most transistor components. Some manufacturers have gotten around the problem by producing transformers which are not much bigger than transistors. But miniature transformers are expensive so most circuits are designed without them. The result may often be a slight loss in gain, but the benefits of size reduction and low cost usually make up for the small gain reduction.

A very frequent requirement in electronics is to connect a circuit to a high-impedance input such as a crystal transducer. Since bipolar transistors have inherently low impedances, FETs are often used for this purpose. In this application, the FET serves very much like a transformer in converting a high impedance to a low impedance.

TRANSISTOR RATINGS

Manufacturers have devised dozens of different specifications to explain the operating characteristics of their transistors. In fact, one major company lists no less than 136 rating symbols. Some of the ratings refer to the maximum limits of a particular device in terms of temperature, voltage, current, and power dissipation. Other ratings describe the capabilities of a device in terms of frequency response, rise time, switching speed, and amplification factor. It is not feasible to our discussion to list all ratings, but some of the more important ratings and their symbols are listed below.

Maximum Ratings

BV_{CBO}	Collector to base breakdown voltage (emitter left open)
BV_{CEO}	Collector to emitter breakdown voltage (base left open)
BV_{EBO}	Emitter to base breakdown voltage (collector left open)
P_C	Maximum power dissipation (collector)
I_B, I_C, I_E	Current (dc) into base, collector, or emitter
T_A °C	Maximum ambient temperature (Celsius)
T_J °C	Maximum junction temperature (Celsius)
T_{STG} °C	Maximum storage temperature (Celsius)
P_T	Power dissipation (usually expressed in watts)

Electrical Characteristics

h_{FE}	Static forward current transfer ratio (dc gain)
h_{fe}	Small signal forward current transfer ratio (ac gain)
I_{CB}	Collector to base current for a specified voltage
I_{CE}	Collector to emitter current for a specified voltage
f_{hfe}	h_{fe} cutoff frequency
f_T	Gain-bandwidth product (frequency at which h_{fe} becomes unity; highest usable frequency)
V_{CEO}	Collector to emitter voltage (base open)
V_{CBO}	Collector to base voltage (emitter open)
V_{BE}	Base to emitter voltage

Most of these maximum ratings and electrical specifications are self explanatory. But to see their real significance, let's use them to interpret the specifications of the RS-2009, a good quality npn switching transistor.

From the transistor's data sheet, we first find that the RS-2009 is an npn silicon epitaxial planar transistor. Since the transistor is made of silicon, this tells us its power dissipation is greater than a similarly packaged germanium unit. And the epitaxial planar construction indicates its frequency response is probably very high.

As the data sheet reveals, we're right on both counts. The RS-2009 can dissipate a maximum of 500 milliwatts (P_T) and the gain-bandwidth product (f_T) is typically 350 MHz. With the transistor's case temperature maintained near room temperature at 25°C, the unit can dissipate up to 1.8 watts.

Going further, we find that the V_{CBO} and V_{CEO} are 60 and 30 volts respectively. The V_{BE} is 5 volts. To prevent damage, the transistor must not be biased at values which exceed these ratings.

The next important specification is h_{FE}, the static forward current transfer ratio or dc current gain. The specifications list values for h_{FE} for various collector currents (I_C) at a V_{CE} of 10 volts. At an I_C of 100 microamperes, for example, the dc current gain is only 35 (minimum) ; at an I_C of 10 milliamperes the h_{FE} increases to a minimum of 75.

The final specifications for the transistor concern is its switching characteristics. We find the RS-2009 has a typical t_{ON} of 25 nanoseconds and a t_{OFF} of 200 nanoseconds.

By now it should be apparent that all these specifications tell us quite a lot about this particular transistor. As the manufac-

turer points out, the RS-2009 has such good f_T, t_{ON}, and t_{OFF} values that it is ideal for switching purposes. And the relatively high values of h_{FE} indicate the transistor should operate well in general purpose amplifier applications.

TRANSISTOR CIRCUITS

Now that we have briefly reviewed some basic electronics and explained some of the more important transistor ratings, we can move into transistor circuits. Three basic circuits are used in most transistor applications. These are called common emitter, common base, and common collector. The term "common" is used to indicate the section of the transistor which is common to both the input and output of the circuit.

The Common-Emitter Circuit

Because of its high-gain characteristics, the common-emitter circuit is the one most often used in amplifier applications. A basic version of the circuit is shown in Fig. 5-3. The circuit diagram shows two power-supply batteries for purpose of clarity. In actual applications the battery between base and emitter, which is included to provide a proper base-bias voltage, is replaced by one or more resistors which borrow current from the remaining battery to accomplish the same purpose.

The input impedance of the common emitter is low (20-5000 ohms), however, and special coupling procedures must be used if the circuit is to be connected to a high-impedance input. A common technique is to employ a preamplifier with high input and low output impedances.

An interesting feature of the common-emitter circuit is that the output signal waveform experiences a phase shift of 180°. That is, a positive-going input signal is negative at the output and a negative-going input signal becomes positive at the output. For this reason, the common-emitter circuit is said to invert an input signal. Inversion does no harm and is even desired for some applications.

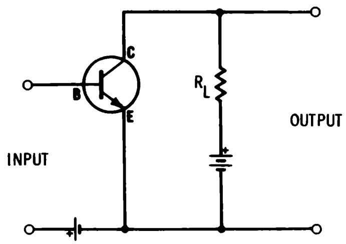


Fig. 5-3. Common-emitter circuit.

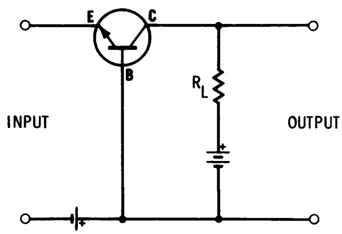


Fig. 5-4. Common-base circuit.

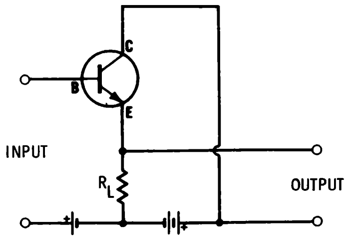


Fig. 5-5. Common-collector circuit.

The Common-Base Circuit

The basic common-base circuit is shown in Fig. 5-4. The chief advantage of the circuit is that its voltage gain is the same as that of the common emitter. Current gain, however, is less than unity giving a power gain (voltage gain × current gain) well below the common emitter's.

While the output impedance of the circuit is high, the input impedance can be lower than the common emitter's. Unlike the common-emitter circuit, the common-base circuit does not invert the signal.

The Common-Collector Circuit

The chief advantage of the common-collector circuit is that it has a much higher input impedance than either of the other two circuits (Fig. 5-5). This is of particular importance in many transistor applications. Voltage gain of the circuit is less than unity and when combined with its current gain, the common-collector circuit gives a power gain less than either of the other two circuits. Often the gain is of little consequence, however, and the common collector can then perform a valuable role as an impedance converter.

The three basic transistor circuits are summarized in Table 5-1. The table is helpful when choosing a circuit for a particular application.

Table 5-1. Characteristics of the Three Basic Transistor Circuits

	Common Emitter	Common Base	Common Collector
Voltage Gain	Yes	Yes	No
Current Gain	Yes	No	Yes
Power Gain	Yes	Yes	Yes
Input Impedance	Medium	Low	High
Output Impedance	Medium	High	Low
Signal Inversion	Yes	No	No

The common-collector circuit resembles an electron-tube circuit called the *cathode follower*. Since their characteristics are so similar, the common-collector circuit is often called the *emitter follower*.

BIASING

For a transistor to operate properly it must be biased. Biasing can be accomplished by means of separate batteries, but it's far more practical to use resistors to borrow current from the transistor's main power supply.

A simple bias arrangement for a common-emitter circuit is shown in Fig. 5-6. The resistor connected between the positive terminal of the power supply and transistor's base forward biases the transistor so that it is slightly on. In this manner an incoming signal can be linearly amplified. If the transistor was not biased, the incoming signal would not turn the transistor on immediately and the signal would not be linearly amplified.

The simple biasing arrangement of Fig. 5-6 provides what is called fixed bias. Unfortunately, the slight difference in transistor characteristics and the sensitivity of transistors to temperature mean that fixed biasing can only be used in very simple applications.

Self-bias can overcome some of the shortcomings of fixed bias. Referring to Fig. 5-7, note that the bias resistor is connected directly from base to collector of the transistor. In effect, self-biasing automatically provides a degree of stabilization by regulating the current through the transistor. If the transistor becomes warm, for example, the collector current increases. This causes the voltage across the bias resistor R_B to drop, thereby reducing the collector current.

The self-bias technique improves temperature stability but at the expense of gain. Gain is reduced since some of the output

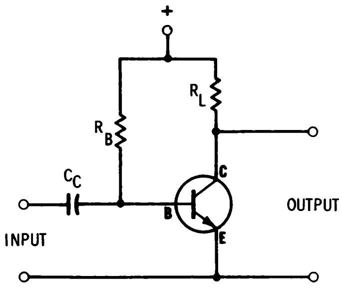


Fig. 5-6. Simple biasing arrangement.

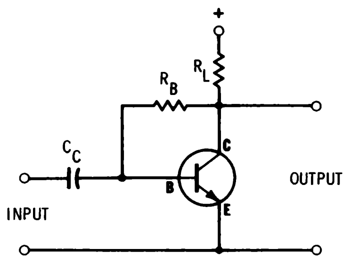


Fig. 5-7. Self-biased amplifier.

signal is diverted back to the transistor's input to regulate the collector current.

A method of achieving stability without significantly reducing gain is shown in Fig. 5-8. Here a resistor is connected between the emitter and ground in order to provide the necessary stability. The capacitor across the resistor permits an incoming signal to be passed without any loss. Without the bypass capacitor, some of the signal would be lost to the emitter resistor. By adjusting the value of the capacitor, the lower frequency response of the circuit can be easily controlled.

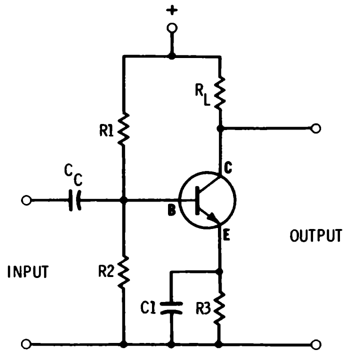


Fig. 5-8. Biasing for increased stability.

Base bias in this circuit is provided by the voltage divider comprised of R1 and R2. The combination of bias and stability offered by this arrangement permits efficient, stable operation of the transistor. The only added expense is a few additional components, and resistors and capacitors are generally very inexpensive.

AMPLIFIER CLASSES

Class A

The transistor amplifier we have been discussing is connected for class-A service. This type of amplifier gives a very linear output. That is, it faithfully reproduces the input signal. However, it is inefficient from a power consumption standpoint. This is because there is always a collector current (because of the base-bias resistor) whether or not an input signal is present. Remember, biasing keeps the transistor slightly on and permits it to operate in the linear region required for distortion-free amplification.

The power consumption of class-A amplifiers is often so small that their inefficiency is of little concern. High-power

output stages, however, require so much power that a second class of amplifier is often employed.

Class B

The class-B amplifier solves the current consumption problem of the class-A amplifier by means of a biasing arrangement which permits only a tiny flow of collector current. A circuit of a class-B amplifier connected for push-pull operation is shown in Fig. 5-9. In operation, both transistors are biased so that there is negligible collector current. The signals appearing at the input transformer's secondary are amplified by the transistor which is forward biased at any one time. The amplified signals are then combined in the output transformer and used, in this case, to drive a loudspeaker.

This is a push-pull arrangement and it permits the advantages of a class-B amplifier to be efficiently utilized. The circuit is often used in the output stage of transistor radios in order to decrease current drain and improve battery life. Push-pull circuits are not limited to class-B amplifiers—and class-B amplifiers need not be connected in a push-pull configuration.

Class C

A third amplifier configuration is designed for use in oscillators and radio-frequency applications. Designated class C, this amplifier is biased so that there is a collector current only when an input signal is present. Unlike the class-B amplifier, class C has no collector current when no signal is present.

Since this kind of amplifier causes an input signal to be badly distorted, it is not used in audio applications. But it's

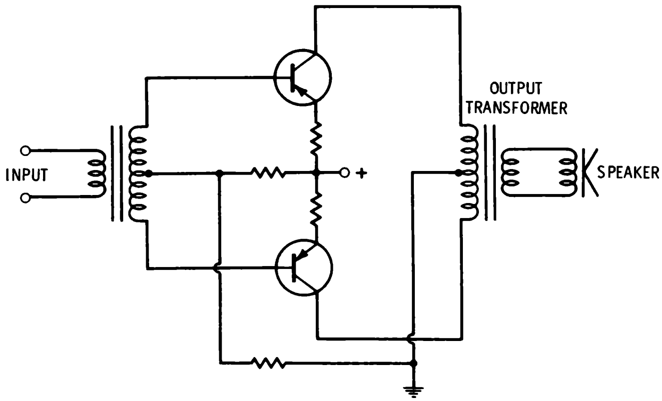


Fig. 5-9. Class-B push-pull amplifier.

ideal for oscillators since waveform distortion is usually of no consequence.

FIELD-EFFECT TRANSISTOR AMPLIFIERS

Bipolar pnp or npn transistors serve well in many amplifier applications. But the availability of low cost, high quality FETs has significantly enhanced amplifier design. The FET, as was noted earlier, has a very high input impedance, low noise, and good high frequency response.

A basic FET amplifier is shown in Fig. 5-10. In operation, an electron current normally flows through the FET from source to drain impeded only by the relatively low channel resistance of a few thousand ohms. A signal at the gate electrode of the FET however, changes the channel resistance and causes the current flow to be modified accordingly.

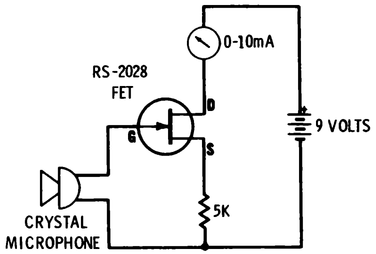


Fig. 5-10. Basic FET amplifier schematic.

It is possible to assemble a simple FET amplifier to better understand its operation. The general layout which uses the same circuit of Fig. 5-10, is shown in Fig. 5-11. The meter is connected in the output circuit to show the effect of an input signal on the source-to-drain current flow. With the parts values shown, the meter should show a current of about 10 mA with no connection to the gate electrode. A current meter is not connected in the gate circuit since the current is so small.

To demonstrate the effect of an input signal at the gate, connect a crystal microphone between the gate electrode and ground. While watching the meter needle, tap the microphone with a pencil. The needle should move slightly toward zero and then return to the previous current level. If an oscilloscope is available, connect it across the meter terminals and speak into the microphone. The scope trace should reproduce the voice waveform.

The gate electrode of most FETs is so sensitive that the output meter needle can usually be moved by merely touching the

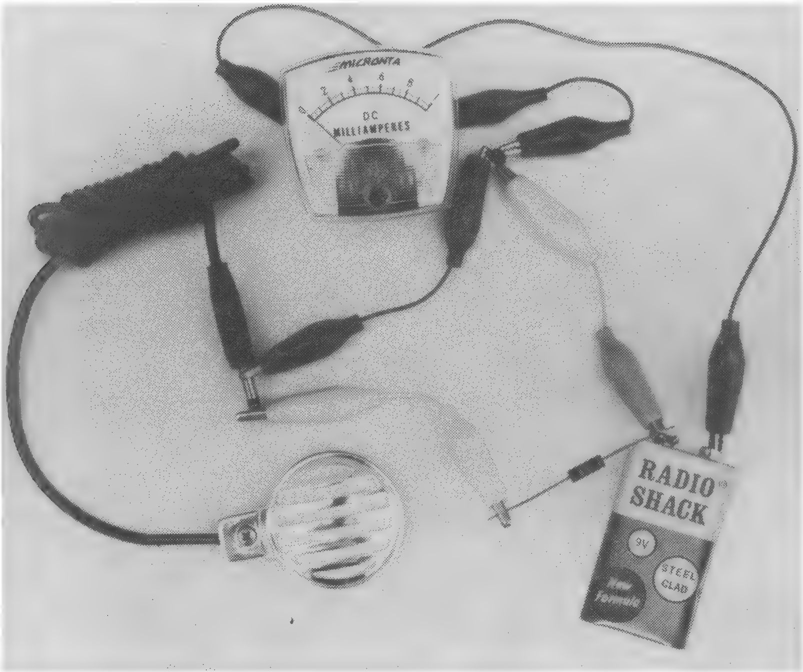


Fig. 5-11. Basic FET amplifier circuit.

disconnected gate lead with a finger. Removing the finger from the gate should also cause a meter movement. The reason for this high sensitivity is body capacity.

In Chapter 2 we discussed the pinch-off or cutoff effect in FETs. This condition occurs when the gate bias is such that the resultant field extends completely across the source-drain channel and literally "pinches-off' the current flow. To demonstrate pinch-off, disconnect the microphone and touch the two input clip leads together momentarily. The meter needle should drop back to almost zero.

In order to make use of their superior high input impedance and low noise characteristics, FETs are frequently cascaded with bipolar transistors. Such arrangements are commonly used in solid-state oscilloscopes, vom's, amplifiers, and mixers.

OSCILLATORS

An amplifier is only one step removed from an oscillator. All it needs is a certain type of feedback. High-gain amplifiers are particularly susceptible to oscillation and circuit designers

go to great lengths to avoid coupling and feedback which will cause an amplifier to oscillate.

When a circuit is designed to oscillate rather than amplify it can perform a variety of useful tasks. Radio frequency generation circuits employ high frequency oscillator circuits, and audio frequency oscillators find use as tone generators, metronomes, alarms, code-practice oscillators, and sirens.

There are several classes of transistor oscillators which produce a waveform with both positive and negative components. Some use a quartz crystal to accurately control the frequency of oscillation. Others use a tuned inductor-capacitor (LC) network to govern the frequency. These basic oscillators can be designed in a variety of configurations.

A special class of transistor oscillators produce nonsinusoidal output waveforms. These oscillators employ resistor-capacitor (RC) or resistor-inductor (RL) feedback to obtain a series of either positive or negative output pulses. The pulses may take the form of narrow spikes, rectangular pulses, or sawtooth waveforms.

A typical example of a nonsinusoidal oscillator is the *multivibrator*. This oscillator employs a back-to-back arrangement of two transistors, one normally on and the other normally off. In operation, the transistors switch one another on and off in sequence, thus producing a square-wave output. Multivibrators are commonly used as pulse generators, pulse stretchers, light flashers, and clocks. Some multivibrators are normally off but are triggered into operation by an external pulse.

A second kind of nonsinusoidal oscillator is called the *blocking oscillator*. This circuit uses inductor-capacitor feedback to achieve a series of brief, widely spaced pulses. Since the inductor used to obtain feedback can be a transformer, the blocking oscillator is often used in dc converter circuits. The unijunction transistor can be used in a third kind of sinusoidal oscillator, but it is so unique it will be described in a separate section.

Unijunction Transistor Oscillators

The unijunction transistor (UJT) can be used in a very simple nonsinusoidal oscillator. The circuit for a typical UJT oscillator is shown in Fig. 5-12.

Operation of the UJT oscillator is identical to that of a neon lamp relaxation oscillator. The neon lamp circuit operates by charging a capacitor through a resistor until the capacitor voltage exceeds the ignition voltage of the lamp. Since the lamp is in parallel with the capacitor, the capacitor discharges

through the lamp causing it to fire. The lamp turns off and the cycle repeats.

The UJT circuit is virtually identical in principle. The major exception is that the neon lamp is replaced by a transistor. Referring to Fig. 5-12, note that capacitor C1 is charged through R1. When the charge on C1 reaches a value which forward biases the UJT emitter, the UJT conducts and C1 discharges through the UJT and R3. R2 helps to stabilize the circuit against adverse effects of temperature changes.

The discharge of C1 is very fast and appears as a spike across R3. The charging time of C1, however, is relatively slow. The slow charge and rapid discharge of C1 is responsible for the sawtooth output.

UJT oscillators are so simple they are widely used as tone generators and for firing SCRs. Recall from Chapter 1 that an SCR is a four-layer device which normally does not conduct. A current spike applied to the gate electrode, however, turns the SCR on as if it were a mechanical switch or relay. Unijunction oscillators are often used to supply the necessary pulse.

We'll describe a UJT circuit which can be easily built by the experimenter in a later chapter. But first let's move on to still another nonsinusoidal transistor oscillator.

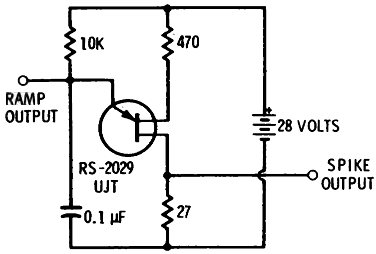


Fig. 5-12. Unijunction oscillator.

AVALANCHE TRANSISTORS

As we noted earlier in this chapter, bipolar transistors are characterized by several different breakdown voltages. BV_{CBO}, for example, stands for the collector to base breakdown voltage. Some transistors are made to be operated in a mode which calls for the BV_{CEO} (collector to emitter breakdown voltage) to be intentionally exceeded for a very brief time. The result is a current spike rising very fast.

Actually, many kinds of transistors can be made to operate in the breakdown or avalanche mode. A circuit which will per-

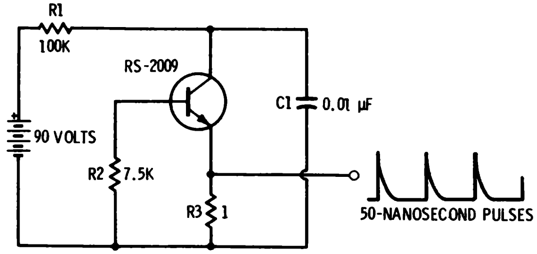


Fig. 5-13. Avalanche transistor oscillator.

mit the RS-2009 transistor to be operated as an avalanche-transistor oscillator is shown in Fig. 5-13. In operation, capacitor C1 charges through R1. Base bias for the RS-2009 is provided by R2. When the charge on C1 exceeds the collector to emitter breakdown voltage, the transistor avalanches and discharges C1 through R3. With the component values shown in Fig. 5-12, a pulse only 50-nanoseconds wide will appear across R3. Since the current is so very high (25 amperes), this kind of circuit can be used to drive semiconductor laser diodes very efficiently.

The reader may wonder why 25 amperes of current does not destroy the transistor. If the current were continuous, the transistor would indeed by destroyed, but the 50-nanosecond pulse is so brief that the silicon forming the heart of the transistor scarcely has time to warm up before the capacitor has been discharged.

SWITCHING CIRCUITS

The nonsinusoidal oscillators we have been discussing bring home a fact brought out in Chapter 2—transistors can be used as switches. In an amplifier, a transistor is operated in the relatively linear region between cutoff and saturation. But in a switching circuit, a transistor is operated in either the cutoff or saturation regions; the linear region in between is ignored. The switching ability of certain transistors makes them very useful in a large variety of digital logic circuits such as flip-flops, gates, and other triggered circuits.

CHAPTER 6

CONSTRUCTION PROJECT FUNDAMENTALS

As we have noted throughout this book, transistors can be used in a wide variety of practical applications. The best way to learn about many of these applications is to actually use transistors in working circuits. Now that we have discussed the theory, manufacture, and characteristics of these little devices, the remainder of this book will be devoted to a variety of simple construction projects. Each of these projects can be assembled in an hour or two by anyone, regardless of electronic experience. No special skills are required, and the cost of each project is quite low.

For ease of assembly and understanding, each construction project includes details on circuit operation, assembly, testing, and applications. For the experimenter desiring to go a little further, each project includes a section describing variations and improvements on the basic circuit. A parts list, circuit diagram, and figures showing the completed circuit greatly simplify construction.

Before actually getting into the construction projects, this chapter will present some hints on electronic assembly and construction. Read this chapter carefully, and then begin work on one of the construction projects presented in the next chapter.

COMPONENT SELECTION

The first step in assembly of an electronic construction project is selecting the various components required for the circuit. There are a variety of sources for electronic parts so this is usually not a difficult procedure. Most of the parts used

in the circuits described in this book, for example, were obtained from Radio Shack.

The parts list for an electronic construction project is not necessarily intended as an exact guide. Substitutions can usually be made and frequently a slightly different component value must be used when the specified value is out of stock or no longer available.

A few general guidelines can be quite helpful when making parts substitutions.

Resistors

Since most electronic construction projects use resistors with a ten- or twenty-percent tolerance, it's generally not harmful to make substitutions within a range of perhaps plus or minus ten percent tolerance from the specified value. For example, if a 10,000-ohm resistor is specified but is not available, values between 9000 and 11,000 ohms should work just as well.

An important exception to these general guidelines for resistor substitution is when a parts list specifically calls for no substitutions. This rarely happens, however, and is usually limited to special-purpose circuits where a resistor value is critical to the calibration of the circuit.

Most low-power transistor circuits use resistors rated at ⅛ or ¼ watt. Higher-power circuits may specify resistors rated at higher wattages, however, and these should always be used.

Capacitors

Like most resistors, capacitor values usually vary from the rated specification. It is not uncommon for a capacitor to have from twice to half its rated value. Because of this wide variation, capacitor values specified in a parts list may be substituted if exact values are not available. For example, it usually does no harm to use a 0.2-μF capacitor for a 0.1-μF unit.

When selecting a capacitor, always make sure it is rated at more than the maximum power-supply voltage. If, for example, a capacitor is rated for operation at 16 volts, it may be destroyed by operation at 30 volts. It's perfectly acceptable to use high-voltage capacitors in low-voltage circuits.

Transistors

In simple transistor circuits it is usually possible to substitute many types of transistors for the one specified, as long as it has the same polarity (pnp or npn). Often simple circuits will simply specify a "general purpose" pnp or npn transistor for a particular application.

The circuits described in this book all use specified transistor type numbers. In most cases, however, substitutions can be made without affecting circuit performance.

In many circuits transistors should only be substituted within a specified class. For example, if a power transistor is specified, a similar type transistor capable of dissipating at least the specified power should be used. If a 20-watt pnp unit is specified, there should be no harm in using a 30-watt pnp transistor.

Other examples where substitutions should be made only within a specific class include high-frequency and switching transistors. An audio-frequency transistor, for example, will not necessarily work properly at frequencies of one megahertz or higher.

Sometimes the semiconductor material used to make a particular transistor is an important limiting factor. In high-temperature applications silicon transistors are almost always preferred over germanium units. Also, germanium transistors are sometimes preferred when a very low collector-emitter ON impedance is desired.

As a final reminder, never substitute bipolar transistors for field-effect (FET) or unijunction (UJT) devices. The substitution just will not work.

Diodes

Diode substitution is usually less critical than transistor substitution. In most circuits specifying a particular diode, literally dozens of types will operate as well as the one specified.

There are, however, important exceptions to this general rule. Some switching and pulse circuits require special-purpose, fast rise time diodes for proper operation. Also power-supply diodes must be rated at least as high as the maximum expected voltage.

Several electronic parts distributors offer bags of ten or twenty diodes for only a dollar so. Sometimes the diodes are manufacturer's rejects, but usually they will work fine in general purpose experimenter applications. Just make sure the diode is rated at the proper voltage before using it in a power-supply application.

A special class of diode which should be substituted with care is the zener diode. Since these diodes are almost always used as voltage-reference devices in power supplies and other circuits, very close or exact substitutions are usually required. Tolerance specifications for zener diodes are usually much tighter than those for typical resistors and capacitors.

POWER-SUPPLY SELECTION

The most convenient power supply for a transistor circuit is the battery. Batteries are readily available, convenient to use, and reliable in most transistor-circuit applications. Furthermore, battery-powered circuits can be operated anywhere and are not restricted by a power cord, as are the line-operated circuits.

On the other hand, line-operated circuits are usually much cheaper to operate than equivalent battery-powered units. The initial cost of the components necessary to convert the ac line voltage into the low voltage dc required to operate a typical transistor circuit is usually more than offset by the relatively high cost of replacement batteries.

The major disadvantage of line-operated circuits is the hazard of coming in contact with 110 volts ac. Careful wiring and assembly practice must always be followed when working with circuits powered by household current. For this important reason the construction projects described in this book are all battery powered.

Most transistor circuits require from 1.5 to 15 volts for proper operation. Practically any battery or arrangement of batteries giving the required voltage can be used.

Penlight batteries are ideal for transistor circuits. They are inexpensive, easily replaced, and a variety of commercial holders are available.

An excellent general-purpose power source for transistor circuits is the nine-volt transistor radio battery. These batteries are commonly available, low in cost, and easy to use. Since they are supplied with snap-type end connectors, they can be quickly removed from a circuit for replacement.

A special class of nine-volt transistor radio battery is the mercury battery. This battery costs far more than the typical nine-volt battery, but its increased lifetime offsets the additional investment. Mercury batteries deliver approximately 8.4 volts instead of 9.0 volts.

READING CIRCUIT DIAGRAMS

Transistor circuits are almost universally shown as *schematics* or circuit diagrams. The schematic is simply a shorthand technique of showing the various components of a circuit and their relationship to one another.

We have already used a number of circuit-diagram symbols in this book to illustrate several types of basic circuits.

There are other component symbols as well, and many of them are described in detail in the *Realistic Guide to Schematic Diagrams,* a Radio Shack publication.

CIRCUIT BOARDS

The circuits described in this book are all assembled on perforated boards so that component placement can be easily visualized. The perforated board is a very convenient medium for constructing a circuit, particularly a prototype or experimental device. If care in layout and wiring is taken a very neat assembly can be made.

Several types of perforated board are available. For most general-purpose construction the alternate grid board used for the projects in this book is ideal. The perforations are close enough to one another to permit easy installation of closely spaced transistor leads. Boards with wider spaced and larger perforations are also available.

Another kind of circuit board is copper-clad phenolic. Copper-clad boards are designed for etched circuits. The etched-circuit board replaces the wiring of conventional circuits with carefully etched strips of copper.

SOLDERING

No matter what method of construction is used, soldering will be necessary to make permanent and reliable connections between components. The beginner should practice soldering scrap lengths of wire together before working with actual component leads. The soldering procedure is as follows:

1. Obtain a soldering iron rated at about 25-40 watts and tin the tip according to the manufacturer's instructions. Keep the tip clean by using a damp sponge or cloth to wipe away accumulated oxidation and foreign matter during soldering. Do not use a soldering gun for assembling transistor circuits, as its high heat output may damage some components, particularly heat-sensitive semiconductors.
2. Always use a good grade of rosin-core solder when soldering electronic components to one another. Never use acid core solder for this purpose as it is highly corrosive and may damage electronic parts.
3. Remove grease, oil, paint, and other matter covering parts to be soldered together. This will insure a good bond between the solder and connection.

4. Begin soldering a connection by first heating the joint to which solder will be applied. When the connection has been heated, leave the iron in place and apply solder to the connection (not the iron).

5. Permit the solder to flow throughout and around the connection for a second or so before removing the iron. Let the connection cool before moving it in any way.

If these five steps are followed, a good solder connection is easily made. A good connection will be shiny and smooth in appearance while a poor connection will look dull.

PACKAGING

Experimental circuits are often built on perforated boards and not enclosed in a housing. This is perfectly adequate for "breadboard" work as it permits components to be changed or switched around within a circuit.

For a more permanent application it's usually desirable to mount a circuit inside a housing. Besides providing protection for the components, the housing provides a convenient base for controls, switches, pilot lamps, and hardware. In addition, circuits mounted inside a housing are more compact and convenient to use than their breadboard counterparts.

Better results can be had by employing enclosures made specifically for use with electronic circuits. Radio Shack offers several such enclosures, including two with a perforated back. These "perfboxes," as they are called, eliminate the need for a separate circuit board inside the enclosure.

TOOLS AND TEST EQUIPMENT

The most valuable tools for electronic construction are a pair of long-nose pliers, a wire cutter, a wire stripper, and a set of screwdrivers. Conventional pliers, files, a set of wrenches, and an electric drill can also come in very handy. As we have already indicated, a soldering iron is absolutely necessary for making permanent and reliable connections.

A relatively good assortment of tools can be purchased for less than $12. Test equipment is another matter and a single instrument can cost far more than a box full of tools.

The most important pieces of test equipment for the electronics experimenter is the volt-ohm-milliammeter (vom). Voms are used for measuring voltage, resistance, and current. They are very handy for checking the resistance of unknown

components, the status of batteries, the polarity of diodes and transistors, and the continuity of wiring connections.

An inexpensive vom is adequate for many test purposes, but for optimum flexibility best results will be had with a high input impedance meter. Older meters used a vacuum-tube input circuit to give the isolation required for high input impedance. These kind of meters are called vtvms for vacuum-tube voltmeters.

More recent high input impedance voms use a field-effect transistor input stage to achieve the high impedance input. They are more convenient to use since they operate from self-contained batteries.

The significance of a high input impedance voltmeter is that readings can be made without significantly affecting the operation of a circuit. This is very important in some (but not all) transistor applications.

The more experienced electronics experimenter will want to obtain an oscilloscope. One of the most versatile pieces of test equipment in electronics, the oscilloscope permits a signal waveform to be displayed on the screen of a cathode-ray tube similar to those used in television sets. While the oscilloscope is virtually a necessity for advanced experimentation, a great deal can be accomplished with the low cost vom.

CHAPTER 7

TRANSISTOR PROJECTS

ONE-TRANSISTOR RADIO

When transistors first became inexpensive enough for home experimenters to purchase, one of the most popular construction projects was the simple one-transistor radio. In the 1950s, dozens of articles on how to construct such radios appeared in magazines specializing in popular science and electronics.

The receiver described here is very similar to those early radios, but that doesn't make it obsolete. This kind of radio is so simple and reliable that it can prove invaluable as an emergency receiver. Unlike the more sophisticated transistor receivers on the market, it will operate from a wide variety of voltages and even a single flashlight cell is capable of powering it. Besides being practical, this project provides a valuable demonstration of the basic principles of a radio receiver.

How It Works

Operation of the receiving portion of the basic one-transistor radio is virtually identical to that of the early cat-whisker crystal radios. The main difference is that this version uses a ready made diode detector rather than the erratic cat-whisker detectors. A circuit diagram of the radio is shown in Fig. 7-1 and the parts list is given in Table 7-1.

In operation, the antenna wire picks up the radio signals and passes them to a resonant circuit composed of a tuning coil and a capacitor. Both of these components are adjustable so the receiver can be carefully tuned for best reception.

The signal passes through the coil and capacitor and all but the resonant frequency is attenuated. The result is that the relatively wide range of frequencies picked up by the antenna are filtered so that only a narrow frequency band remains. The

frequency which passes through the coil-capacitor circuit can be easily varied by merely changing the value of either or both these components. The selected frequency leaves the circuit and passes through a semiconductor diode. The signal is composed of both positive and negative components and is therefore a kind of alternating current. The diode rectifies the signal so that it is composed of a series of positive pulses which are representative of the audio signal carried by the transmitted frequency.

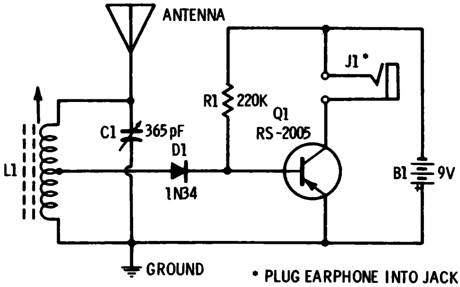


Fig. 7-1. One-transistor radio circuit diagram.

It's possible to connect an earphone between the output of the diode and the ground side of the coil and hear the signal. In fact, this is how the early crystal sets operated. But the signal is so small that the volume is not very high.

The rectified (detected) signal can be increased in volume by means of a single transistor connected as a common-emitter amplifier. In the receiver described here, an RS-2005 pnp transistor (Q1) is used to amplify the signal. Base bias for the transistor is supplied by R1. The output signal is sent to a miniature magnetic earphone which converts the electrical fluctuations into an audio signal.

Table 7-1. One-Transistor Radio Parts List

Item	Description
B1	9-volt battery
C1	Miniature tuning capacitor (530 kHz to 1600 kHz)
D1	Diode (1N34)
J1	Phone jack
L1	Ferrite loop antenna coil
PH1	Magnetic earphone
Q1	Pnp transistor (RS-2005)
R1	220K resistor
Misc	Perforated board, battery clip, wire, solder

Circuit Assembly

The prototype one-transistor radio was assembled on a perforated board. The construction is fairly straightforward. First, bore a single 5/16-inch hole into the board for mounting the variable capacitor. Then enlarge two of the board's holes to a diameter of 1/8 inch with a reamer or drill for installation of the tuning coil. Next, drill a 1/4-inch hole for the earphone jack. Fig. 6-2 shows how the various components can be placed.

When all the mounting holes have been completed, mount the bracket for the tuning coil on the board. Insert the adjustable end of the coil into the bracket so that the two mounting clips snap in place.

Next, install the variable capacitor. Remove the knob by turning the inset to the left until it lifts out. Secure the variable capacitor in place with its mounting nut, and replace the knob with its threaded insert.

The miniature jack is mounted next. As with the variable capacitor, use the nut supplied with the jack to secure it in place.

Finally, mount D1, Q1, and R1 following the layout shown in Fig. 7-2. Solder the various component leads to one another. Short lengths of wire must be soldered to the tuning coil if the component leads are not long enough to reach the coil lugs. The completed project is illustrated in Fig. 7-3.

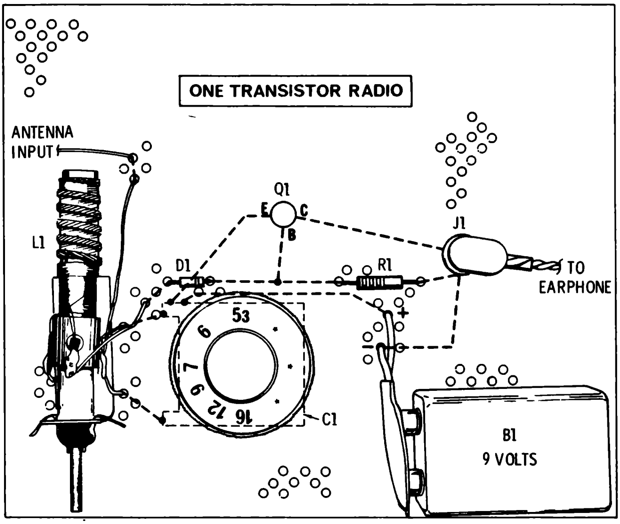


Fig. 7-2. Component placement.

Testing and Operation

To test the operation of the one-transistor radio, connect the antenna lead of the coil to a good external antenna. Ideally, 25 feet of copper wire could be used for an antenna. If this is not convenient try connecting the antenna lead to the metal dial-stop on a dial telephone. The telephone wiring will then act as an external antenna.

When the antenna is connected, plug the earphone into the jack and connect a 9-volt battery to the battery clip. Then slowly rotate the variable capacitor knob until a station is heard. If no station is heard, try rotating the adjustment screw of the tuning coil until the ferrite core inside the coil form is approximately midway in the coil. Rotate the capacitor knob again until a station is heard.

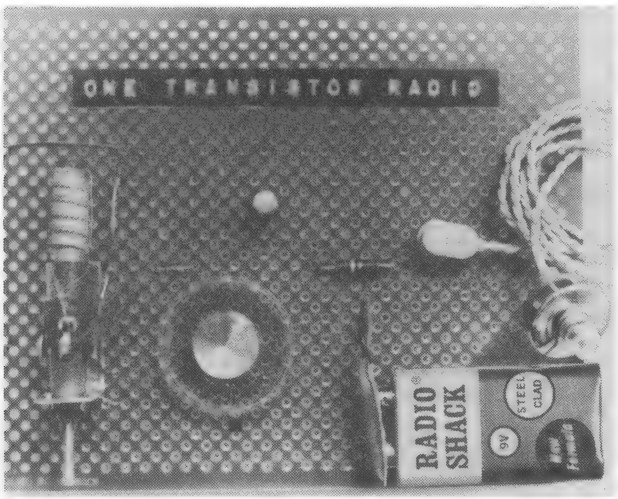


Fig. 7-3. Completed one-transistor radio.

When the radio is operating, the variable capacitor can be calibrated. This procedure will permit stations to be accurately tuned. First adjust the tuning coil slug so it is approximately centered inside the windings. Then turn the variable capacitor knob to the far right and place a small mark under the number 16 on the dial.

To check the calibration, tune in a station of known frequency and see if the number on the dial approximately matches the marker point. If not, readjust the tuning coil until a match is made.

Going Further

A number of improvements can be made to the basic one-transistor radio. First, some diodes operate better than others as radio detectors. While most general purpose silicon or germanium diodes will work fine in the circuit, a few may operate considerably better than others. Selecting an optimum diode is a simple manner. Connect several into the circuit one after another while listening to a station with the earphone. The diode that gives the loudest signal is then soldered into the circuit.

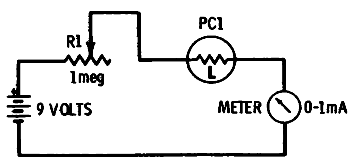
TRANSISTORIZED LIGHT METER

Using but a single transistor such as the RS-2001 (2N1304), it's possible to construct a very sensitive light meter. The meter can be used for general purpose experimentation or calibrated and used for photographic purposes. The meter uses a total of only four components: photocell, transistor, potentiometer, and milliammeter. The components were mounted on a perforated board for the prototype circuit, but they can easily be housed in a small plastic case if desired.

How It Works

Operation of the light meter is dependent on a photocell which changes its resistance when exposed to light. The photocell used here is the photoconductive type. That is, it increases or decreases its resistance according to the amount of light striking the cell. The dark resistance of the cell used here is normally very high, perhaps 5000 megohms or more. When the light level is increased, the photocell's resistance drops considerably and may be but a few hundred ohms at high illumination levels.

Fig. 7-4. Basic light-meter circuit.



It is possible to make a working light meter with a photocell, meter, and battery. A circuit for this kind of light meter is shown in Fig. 7-4. But this kind of circuit is not very sensitive to very low light levels unless an extremely sensitive current

Table 7-2. Transistorized Light-Meter Parts List

Item	Description
B1	9-volt battery
M1	0-1 milliammeter
PC1	Photocell (5000 megohms dark resistance)
Q1	Npn transistor (RS-2001)
R1	1-megohm potentiometer
Misc	Perforated board, battery clip, wire, solder

meter is used. Such meters are expensive and their movements are inherently fragile.

A better approach is to use a transistor to amplify the current and use the amplified current to drive a relatively inexpensive meter. In this manner very low light levels can be easily measured using a milliammeter.

The circuit for the transistorized light meter is shown in Fig. 7-5 and the necessary parts are listed in Table 7-2. In operation, the light striking photocell PC1 decreases the photocell's resistance and permits a larger current to flow. This current, which may be very small at low light levels, is amplified by Q1 which is connected in a common-emitter configuration. The 9-volt battery supplies bias voltage for both the photocell and transistor. The value of the amplified current is indicated on the milliammeter.

Since various photocells have different characteristics, potentiometer R1 is included to permit the circuit to be calibrated. The potentiometer is in series with the photocell and permits the current flow to be adjusted under a set light condition.

Circuit Assembly

The prototype light meter was assembled on a perforated board. Follow the layout shown in Fig. 7-6 when assembling

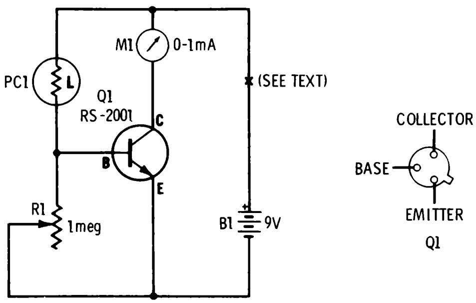


Fig. 7-5. Transistorized light-meter circuit.

the circuit. The transistor is mounted by merely inserting its three leads through the holes in the board and bending them outward on the rear of the board. The potentiometer is mounted by soldering two 2-inch lengths of wire to the center terminal (rotor), and two to the outer terminal (stator) and inserting the wires through the board. For a sturdier mounting arrangement, a $\frac{3}{8}$-inch hole can be drilled through the board and the potentiometer mounted in place with its retaining hardware.

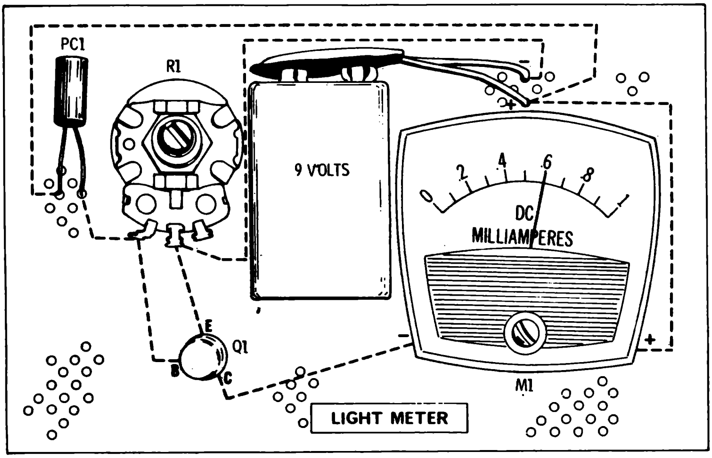


Fig. 7-6. Transistorized light-meter layout.

The meter is mounted by slightly enlarging two holes in the board and securing it in place with the terminal screws. As with the potentiometer, a sturdier mount can be provided by cutting a circular hole in the board and anchoring the meter in place with its four mounting screws. Finish installing the components. Fig. 7-7 illustrates the completed project.

Testing and Operation

Check all wiring to make sure there are no errors and then connect a 9-volt battery to the battery clip. Make sure the room lights are dimmed before connecting the battery to prevent the meter needle from being slammed.

When the battery is connected, slowly point the sensitive end of the photocell toward a source of light. As the cell is pointed toward the light, the meter needle should advance up the scale. If the needle does not advance, try rotating the potentiometer's rotor to increase the circuit's sensitivity.

When the light meter is operating properly try pointing it at a variety of light sources. The meter needle will swing to the far right off its scale if the light is too bright. To prevent this, adjust the sensitivity potentiometer downward.

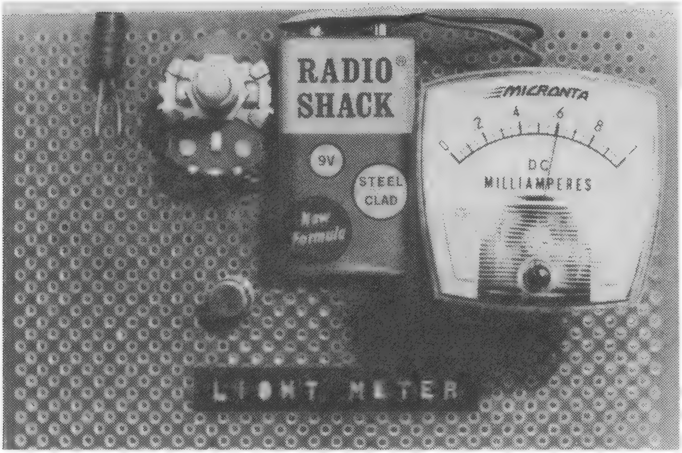


Fig. 7-7. Completed transistorized light meter.

Going Further

While the perforated board used to assemble the light meter is adequate for general purpose experimentation, better results will be obtained by assembling the circuit inside a small plastic or metal box. This construction technique will permit the light-sensitive photocell to be mounted inside a dark-colored tube which will help alleviate the adverse effect of bright lighting. The tube can be made from a painted section of a plastic soda straw or a short length of metal tubing.

Another big advantage of housing the light meter inside a small case is convenience. The sensitivity control can be easily calibrated by simply using a marking pen to indicate the various sensitivity zones through which the control rotates. Also, the battery is easier to mount in a fixed position and does not flop about as when mounted to a perforated board without using a battery holder.

To install the circuit in a small box, cut a strip of perforated board one-inch wide and about three-inches long. Mount the photocell and transistor on one end of the board so that the photocell points toward the end of the board. Mount the potentiometer in a $\frac{3}{8}$-inch hole bored into the box and wire it to the circuit board. The meter should also be mounted in a hole cut into the case. Secure it in place with the four mounting

screws and use short lengths of wire to make the connections to the circuit board.

The battery can be mounted in place by simply using a rubber band to hold it against the bare portion of the circuit board. If the inside of the box is so large that the completed assembly does not remain in a fixed position, use a few screws and nuts to secure the circuit board in place.

DARK-ACTIVATED LAMP

An interesting circuit with a very practical application is the dark-activated lamp. The circuit incorporates a light-sensitive photocell whose operation is identical to that of the cell employed in the light meter.

Operating from two penlight cells, the dark-activated lamp can be used as a night light or even as a limited use intrusion alarm. The circuit is easily assembled in less than an hour.

How It Works

Operation of the circuit involves operating an RS-2009 (2N2222) npn transistor, as a saturated switch. The ability of transistors to switch from a nonconducting to highly conducting state is one of their most important characteristics. Switching transistors are used in logic circuits, nonsinusoidal oscillators, and in applications like the dark-activated switch where low cost, efficient electronic switching is required.

The dark-activated switch is shown schematically in Fig. 7-8 and the parts for construction are given in Table 7-3. It operates as follows. When light falls on the photocell, its resistance lowers and Q1 (the RS-2010 or 2N2484 transistor) is turned off. When Q1 is off, Q2 receives no base bias and it is also turned off.

When the photocell receives sufficient darkness to significantly raise its resistance, Q1 becomes properly biased and

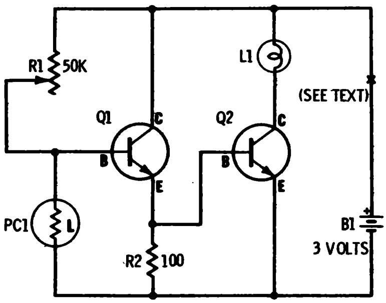


Fig. 7-8. Dark-activated lamp schematic.

begins to turn on. Q2 then receives base bias through the collector-emitter circuit of Q1 and also turns on. Since the resistance between the collector and emitter of Q1 is considerably lowered when Q1 is turned on, Q2 usually goes directly into saturation. This causes the output lamp to turn completely on. Only by carefully adjusting the light falling on the photocell can the lamp be made to come partially on.

Table 7-3. Dark-Activated Lamp Parts List

Item	Description
B1	Two 1.5-volt AA penlight cells
L1	3-volt lamp
PC1	Photocell with a dark resistance of 5000 megohms
Q1	Npn transistor (RS-2010)
Q2	Npn transistor (RS-2009)
R1	50K potentiometer
R2	100-ohm resistor
Misc	Perforated board, battery holder, wire, solder

Sensitivity of the dark-activated lamp is controlled by potentiometer R1. Together with photocell PC1, it forms a voltage divider whose adjustment determines the conduction in the collector-emitter circuit of Q1.

Circuit Assembly

The prototype dark-activated lamp is assembled on a perforated board. To duplicate the assembly, install the parts as shown in Fig. 7-9, and use the component leads or separate wires to connect the components to one another.

The sensitivity control potentiometer can be installed as shown, but a sturdier arrangement can be made by boring a ⅜-inch hole in the board and securing the potentiometer in place with its mounting hardware. The battery holder can be anchored in place with glue, or fastened to the board with wire.

The prototype's lamp is simply soldered in place. For a more efficient arrangement, however, use a socket to facilitate mounting and replacement of the lamp.

When installing the circuit in a case, be sure to wire in a switch at point "X" in the circuit diagram of Fig. 7-5. Potentiometers are available with built-in switches, but better results will be had by using a separate switch. This will prevent the need for readjusting the sensitivity control each time the unit is turned on. Fig. 7-10 illustrates the completed project.

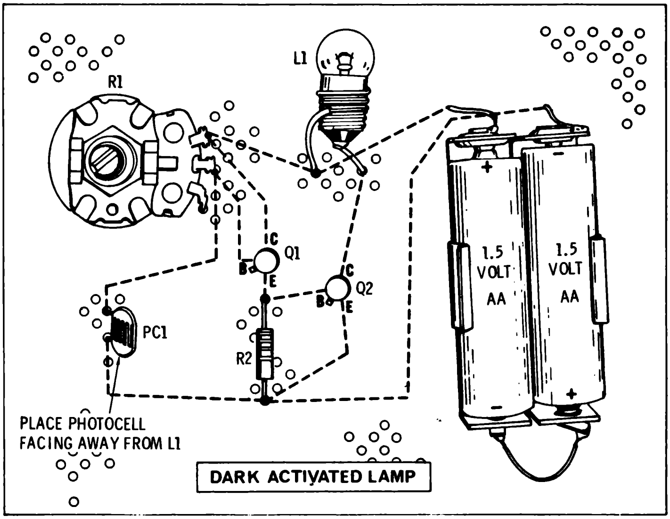


Fig. 7-9. Dark-activated lamp pictorial.

Testing and Operation

Carefully check all wiring and then place the dark-activated lamp circuit in a lighted room. A fair amount of illumination should be permitted to fall on the sensitive face of the photocell. Next, using care to observe correct polarity, insert two size AA penlight cells in the battery holder. This will turn the circuit on.

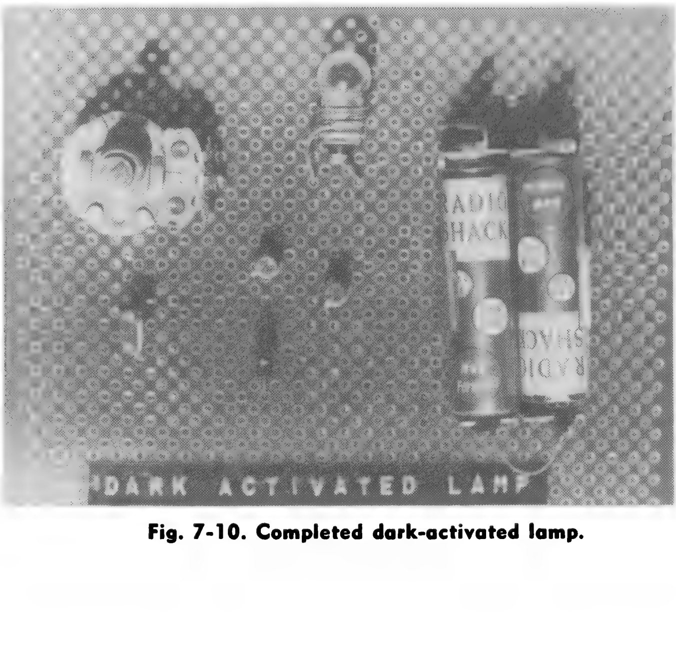


Fig. 7-10. Completed dark-activated lamp.

When the batteries are installed, slowly rotate the potentiometer's shaft until the lamp turns on. When the lamp turns on, back up on the control until it turns off. If the lamp is on when the batteries are installed, rotate the potentiometer until it turns off.

When the sensitivity control has been adjusted so that the lamp is off, turn the room lights off. If there is no direct light on the photocell, the lamp should now turn on. If it fails to turn on it may be necessary to readjust the sensitivity control. A flashlight can be very helpful if this is the case. Simply dim the room lights so that the light sensitive face of the photocell receives no direct illumination and use the flashlight to simulate lighted and nonlighted conditions.

During calibration of the circuit, the lamp may become excessively bright when adjusting the sensitivity control. This is especially likely to occur if a lamp rated at a lower voltage than that supplied by the batteries is being used. If this occurs, be sure to turn the control shaft back to a point where the lamp is less bright to prevent it from being burned out. Ideally, use a lamp rated at the voltage supplied by the batteries used to power the circuit.

Going Further

As mentioned earlier in this chapter, the dark-activated lamp can be a very practical circuit. At times, it may be necessary to keep extraneous light away from the photocell. This is easily accomplished by placing a small tube over the photocell as shown in Fig. 7-11 so that only light from the outside can reach the cell's light sensitive surface.

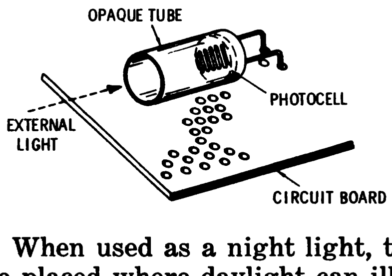


Fig. 7-11. Photocell light shield.

When used as a night light, the dark-activated lamp should be placed where daylight can illuminate the photocell.

To use the dark-activated lamp as an intrusion alarm, mount it in a place where the beam from a light source can be projected across an access way. With the beam illuminating the photocell, the lamp will be off. But when the beam is broken the lamp will flash on.

The intrusion alarm configuration can be used to announce visitors, customers, or unwanted intruders. A variation of the circuit is described in a later chapter. This circuit provides an output relay which stays on when a light beam is broken. It is better suited for some intrusion alarm applications since the relay contacts can be used to operate a bell or buzzer.

LIGHT-ACTIVATED RELAY

As we have seen in the two preceding chapters, light-sensitive photocells can be paired with transistors to give a variety of useful electronic circuits. In this chapter we will describe still another of these circuits, a relay which is activated by an external source of light. The circuit is unique in that the relay can be connected to stay on once it is activated. As in the previous light-activated circuits, the light-activated relay includes a potentiometer as a sensitivity control.

How It Works

A simple common-emitter transistor amplifier is the heart of the light-activated relay circuit.Table 7-4 lists the parts necessary for construction. Referring to the circuit diagram of Fig. 7-12, note that when the resistance of the photocell is high, little base current can flow in transistor Q1. When the photocell is illuminated by a light source, its resistance is significantly lowered and transistor Q1 is biased into saturation. The resultant collector-emitter current is sufficient to pull in the relay and activate an externally controlled device. Resistor R2 is necessary to limit the current through the transistor to keep it from overheating when the relay is pulled in. R2 also limits the current through the relay coil.

Fig. 7-13 shows how the circuit should be connected if it is desired to keep the relay on once it is activated. The "normally open" contact of the relay is connected to the lower relay coil

Table 7-4. Light-Activated Relay Parts List

Item	Description
B1	9-volt battery
PC1	Photocell with a dark resistance of 5000 megohms
Q1	Npn transistor (RS-2010)
R1	25K potentiometer
R2	27-ohm resistor
Relay	Spdt 6-mA, 500-ohm relay
Misc	Perforated board, battery clip, wire, solder

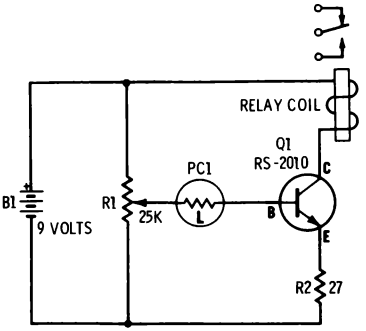


Fig. 7-12. Light-activated relay circuit diagram.

contact. When the circuit is activated the relay latches and stays in that state until the reset switch is pressed.

By the way, R3 must be included in this version of the circuit in order to limit current through the relay coil to the rated value and preserve battery life.

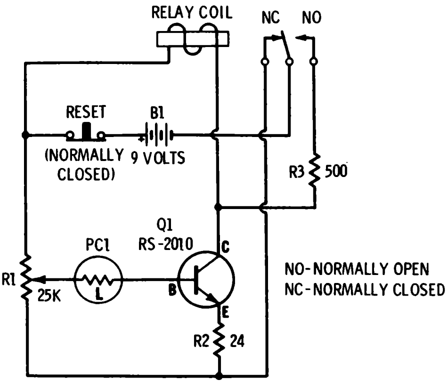


Fig. 7-13. Latching circuit.

Circuit Assembly

The components are all mounted by means of their connection leads, with the exception of the sensitivity control potentiometer. The potentiometer was mounted by soldering 2-inch long connection wires to each of its three terminals and using them to hold the potentiometer in place. As with the other circuits which use potentiometers, the sensitivity control can be mounted more firmly by drilling a ⅜-inch hole in the perforated board and installing the potentiometer in the hole with its mounting hardware. Fig. 7-14 shows a pictorial of the light-activated relay project.

Practically any general purpose transistor can be used in the amplifier portion of the circuit. While the RS2010 used for Q1 in the prototype circuit is an npn unit, a pnp transistor can be used by simply reversing the battery connections.

Note that the prototype light-activated relay shown in Fig. 7-15 uses a black tube over the photocell. The tube acts to shield the cell from ambient light so the circuit can be controlled by the light from a flashlight even in a normally lighted room.

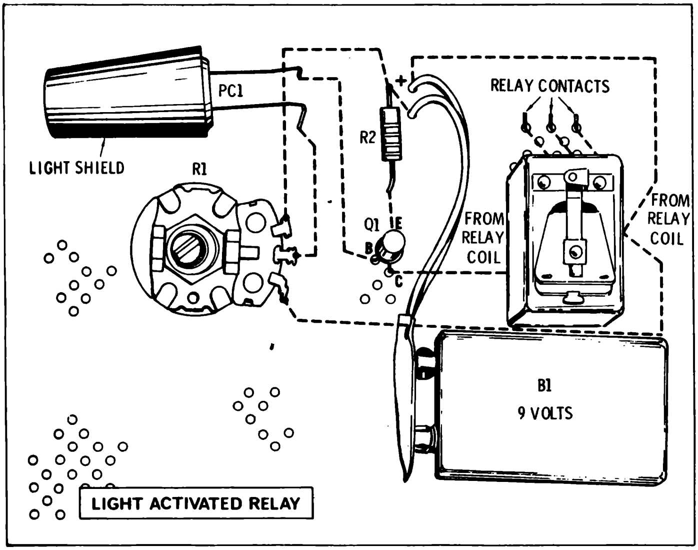


Fig. 7-14. Light-activated relay pictorial.

As with the previous two circuits, many types of photocells will work with the light-activated relay. For best results, however, use a cell with a large dynamic range. A cell with a very high dark resistance and very low light resistance is ideal. For optimum operating results several different cells can be tried.

Testing and Operation

To test the circuit for proper operation, set the sensitivity control at about the midpoint and clip a 9-volt battery to the battery connector. At this point the relay should not be activated. But if it is, adjust the sensitivity control until it drops out. Make sure the photocell is not brightly illuminated, of course, or the relay will tend to activate.

When the circuit has been adjusted so that the relay is not activated, point a flashlight toward the photocell's light-sensi-

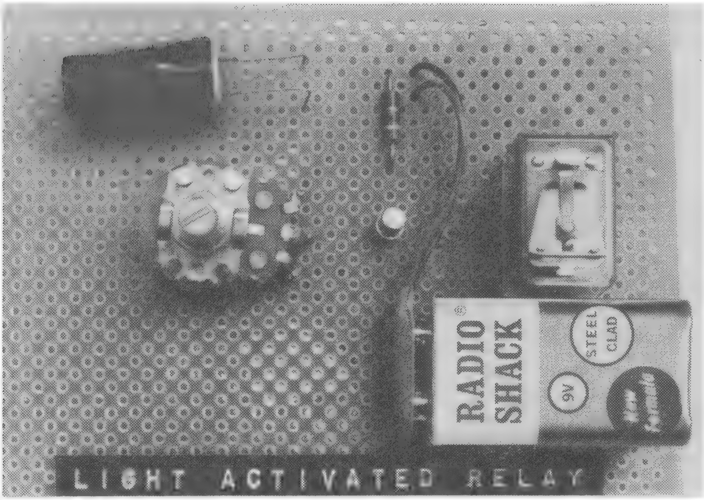


Fig. 7-15. Completed light-activated relay.

tive surface. The relay should immediately activate. If it does not pull in, adjust the sensitivity control until proper operation is achieved. Activation of the relay can be observed by watching the moving central contact. The contact will move down and make a distinct click when the relay "pulls in."

When using the light-activated relay in the latching mode (Fig. 7-13), it will be necessary to push the reset button so that the up and down motion of the central contact can be observed. If this isn't done, the relay will remain activated (latched) once it turns on.

When the circuit (Fig. 7-12) is working, test it for proper operation by moving the light source toward and away from the photocell. If the sensitivity control is properly adjusted the relay should click in each time the light strikes the photocell.

Going Further

The light-activated circuit can be used in a variety of practical applications. But first it should be built into a small case so it can be conveniently used. As with the previous circuits this is easily done by installing the components on an appropriately sized circuit board. Make sure the photocell is placed where it can be exposed to external light. To keep it from triggering from the room lights, it is a good idea to put a small opaque tube around the photocell, such as the one shown in the preceding chapter.

An interesting application for the relay is to connect it as an automatic annunciator. By shining a light across a door or other entrance, the relay will trigger a bell or buzzer when a visitor breaks the light beam. To connect the relay for this application use the circuit diagram shown in Fig. 7-16.

When the relay is connected in the latching mode (Fig. 7-13), it can be used as an intrusion alarm. When the light beam is broken, the relay contacts will remain pulled in and an external bell or buzzer will stay turned on until the reset switch is activated. The reset switch momentarily turns the circuit off and permits the photocell to once again initiate activation of the relay.

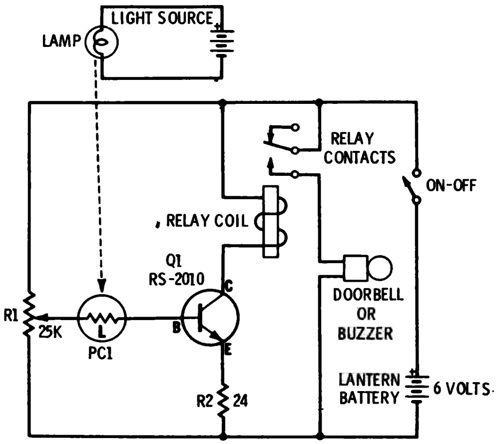


Fig. 7-16. Relay used as automatic annunciator.

UNIJUNCTION TIMER

Unijunction transistors are ideal for use in pulse generators and precision timers. The timer described here has an adjustable delay ranging from less than a second to thirty seconds or more. The circuit is actually a unijunction oscillator with an adjustable time constant.

Operation of the timer is simple and reliable. To begin a timing cycle, a start switch is activated. Then, after a preset interval, the unijunction transistor (UJT) issues a pulse with sufficient amplitude to pull in a sensitive relay. The relay is connected so that its contacts keep the relay activated until a reset switch is activated.

Applications for the UJT timer are numerous. It can be housed in a small plastic box, for example, and used to trigger

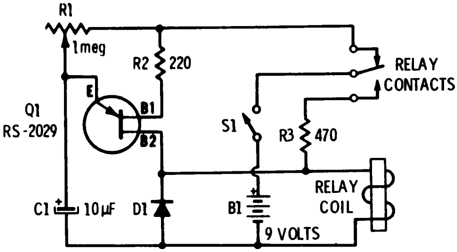


Fig. 7-17. Unijunction timer circuit diagram.

a warning light every thirty seconds for long distance calls. By connecting the relay contacts to a bell or buzzer, the unit can be used as a darkroom timer. The unit can also be used in various experimental applications.

How It Works

The parts necessary for construction of the UJT timer are given in Table 7-5. Operation of the circuit can be determined by referring to the circuit diagram in Fig. 7-17. In operation, capacitor C1 charges through potentiometer R1 until the UJT, an RS-2029, fires. When the UJT fires, C1 discharges through the UJT and the relay coil. The pulse activates the relay, and the relay is kept in a latched position by using its normally open contacts (which are turned on by the activation pulse) to supply driving voltage to the coil. The timer is reset for another timing cycle by turning it off for a moment (S1). R3 is used to limit the current through the relay coil. Without R3, excessive current will flow through the coil and possibly cause its destruction. Also, battery life will be significantly shortened. The diode (D1) is used to short circuit any high voltage pulses which may be generated when the UJTs firing pulse

Table 7-5. UJT Timer Parts List

Item	Description
B1	9-volt battery
C1	10-μF, 15-volt capacitor
D1	Diode (1N914)
Q1	Unijunction transistor (RS-2029)
R1	1-megohm potentiometer
R2	220-ohm resistor
R3	470-ohm resistor
Relay	Spdt 6-mA, 500-ohm relay
S1	Spdt switch
Misc	Perforated board, battery clip, wire, solder

rapidly falls off. Such a pulse frequently occurs when a voltage across a coil is suddenly removed. The voltage in the coil rapidly collapses and induces a very high voltage spike through the coil's windings. Without a protection diode to absorb the voltage pulse, the UJT might be permanently damaged.

R1 and C1 form the timing part of the circuit. When R1 is set to a relatively high value, C1 takes more time to charge to the circuit's firing voltage. When R1 is set to a low value, C1 charges are more rapid and briefer timing periods are obtained. The timing periods can be made very brief (less than a second) by decreasing the value of C1 to about 10 μF and making appropriate adjustments of R1. If C1 is made much smaller than about 10μF the timer's firing pulse may be too brief to pull in the relay.

Circuit Assembly

Install the components on the board and solder the leads in place as shown in Fig. 7-18. Do not install capacitor C1 at this time.

The relay is installed by passing its flexible leads through the circuit board and bending them flat against the rear of the board. Cut the leads to the minimum length necessary to reach their connection points in order to keep the relay firmly against the circuit board.

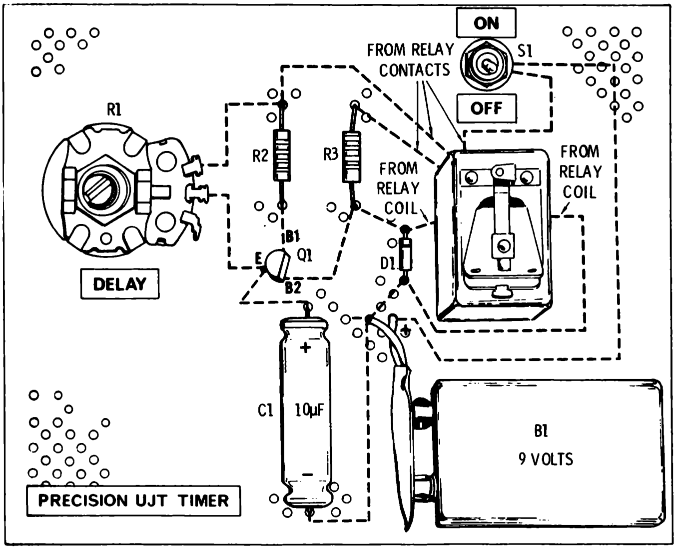


Fig. 7-18. Unijunction timer pictorial.

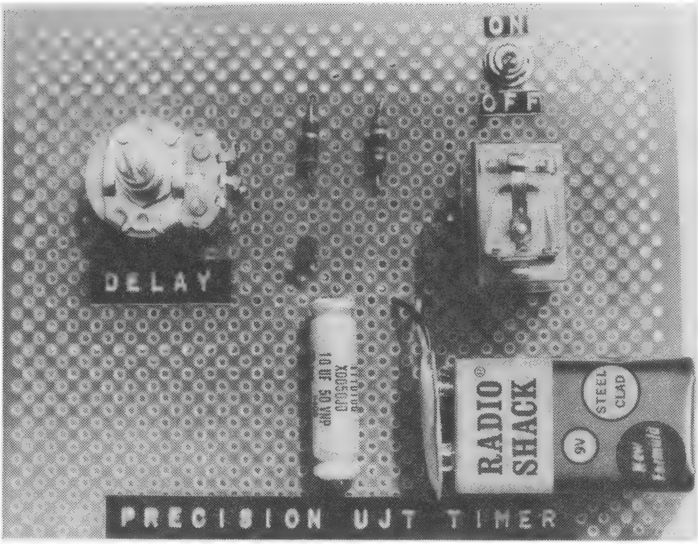


Fig. 7-19. Completed unijunction timer.

When the relay and all remaining parts are in place, the capacitor can be installed. If relatively long delays are required, use a 100-μF capacitor rated at 25 volts. If short delays are required, proceed to the section on testing and operation for further instructions. The completed project is illustrated in Fig. 7-19.

Testing and Operation

Test the timer by connecting a 9-volt battery to the battery clip and adjusting R1 until the relay activates. When the relay latches on, turn the power switch (S1) off and then on again to reset the circuit. Try adjusting R1 to see the minimum and maximum time delays which can be obtained.

If very short time delays are required C1 should be less than 100 μF. In the prototype circuit a 10-μF capacitor produced time delays of as little as a tenth of a second. A capacitor with a value much less than 10 μF may produce a trigger pulse too brief to operate the relay. Capacitor values between 10 and 100 μF can be selected to give a variety of timing periods.

Going Further

The precision timing circuit can be easily modified for a variety of different uses. We have already described the simplest modification—varying C1 to permit very brief timing

periods. To exploit the wide range of timing periods available with several different timers, it's easy to connect several capacitors in the circuit and use a low cost rotary switch to select the appropriate one to give the desired timing period.

To ease adjustment of the timer, it should be calibrated against a known time reference. This is easily accomplished by rotating the time-delay adjustment potentiometer while making appropriate timing marks at various settings. Several sets of marks can be made if more than one capacitor is used.

UNIJUNCTION TONE GENERATOR

Electronic tone generators are used for a variety of purposes. By using a telegraph key for a switch, a tone generator can be used as a code practice oscillator. They are frequently employed in warning indicators. And most tone generators are also well suited for use as signal generators in radio, television, and amplifier troubleshooting.

The unijunction transistor relaxation oscillator is ideal for use as a tone generator. It uses few components and those that are required are very inexpensive. This chapter describes the assembly of a UJT tone generator which can be adapted for a variety of applications. Assembly time for the basic oscillator should be well under an hour, making this one of the quickest projects in this book.

How It Works

Operation of the unijunction transistor in a relaxation oscillator mode is described in Chapter 4. The operating principle of this kind of relaxation oscillator can be seen by referring back to Fig. 4-7. A capacitor (C1) is charged through a charging resistor (R1) until the capacitor voltage reaches the emitter-B1 breakdown voltage. Until this point is reached the "diode" formed by the emitter-B1 junction is reverse biased and does not conduct. But when the capacitor's charge reaches the proper value, the emitter-B1 junction becomes forward biased. The junction then switches on and the capacitor discharges through R3 in a very rapid pulse.

When the capacitor is discharged, the emitter-B1 junction is again reverse biased. The UJT does not conduct so the capacitor once again begins to charge. The cycle repeats itself continuously in what is known as a relaxation oscillator mode.

In order to utilize the basic UJT oscillator as a tone generator, R3 in Fig. 4-7 is replaced by the coil of a magnetic speaker. The result is shown in Fig. 7-20. As the capacitor discharges

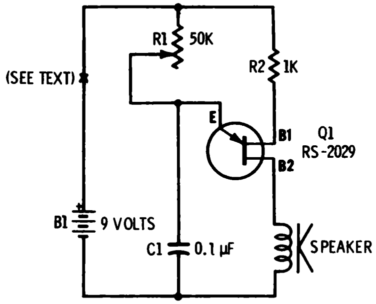


Fig. 7-20. A UJT tone generator circuit diagram.

through the speaker, the speaker converts the electrical signal into sound.

The frequency of the tone can be varied by simply changing the value of R1. Since R1 governs the charging time for C1, the repetition rate is easily varied. The frequency can also be altered by changing the value of the capacitor. Smaller values will give higher frequencies while larger values will result in lower frequencies. The difference in frequency is due to the increase in charging time required of larger value capacitors. Also, with the larger value capacitors the tone amplitude may be increased over that of small value capacitors. This is because the longer discharge time of larger value capacitors produces a wider pulse through the speaker coil and, therefore, a larger audio pulse.

Circuit Assembly

The parts for the UJT tone generator are given in Table 7-6. It can be assembled on a perforated board (Fig. 6-16) or in a small plastic or metal case. Whichever technique is used, the wiring is straightforward and uncomplicated. The most important consideration is to make sure the unijunction transistor is connected properly.

Potentiometer R1, which is included to give a variable tone capability, can be mounted in a ⅜-inch hole bored in the board.

Table 7-6. UJT Tone Generator Parts List

Item	Description
B1	9-volt battery
C1	.1-µF capacitor
Q1	Unijunction transistor (RS-2029)
R1	50K potentiometer (271-1716)
R2	1K resistor
Speaker	8 ohms
Misc	Perforated board, battery clip, wire, solder

Use 1.5-inch lengths of hook-up wire to make the connection to the control's central (rotor) and one outer (stator) terminals. If desired, the potentiometer can be secured to the top of the board by these connection leads.

The speaker is connected to the oscillator by means of two lengths of wire. If the tone generator is to be used for limited experimentation, the speaker does not need to be mounted to the board. But if the circuit is to be used for a practical purpose, it's a good idea to mount the speaker behind the perforated board or in a protective enclosure. By mounting the speaker behind the board, its delicate paper cone will be protected from damage, and the tone it generates can escape through the perforations in the board.

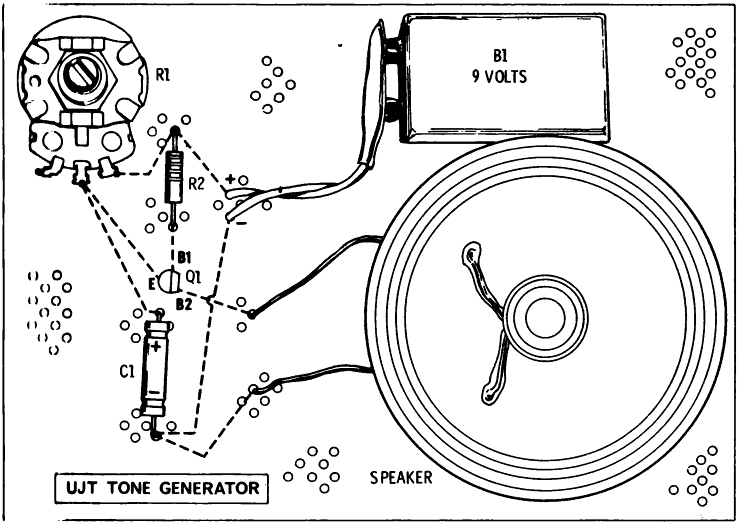


Fig. 7-21. A UJT tone-generator pictorial.

A standard 9-volt battery clip can be used for mounting the battery. Since the oscillator can be turned off by simply removing the battery, a switch is not needed. One can be installed, however, by connecting it at point "X" in the circuit diagram of Fig. 7-20. Fig. 7-22 illustrates the completed project.

Testing and Operation

When the oscillator has been assembled, recheck the wiring to make sure there are no errors. Then snap a 9-volt battery to the battery connector. A tone should be heard from the speaker.

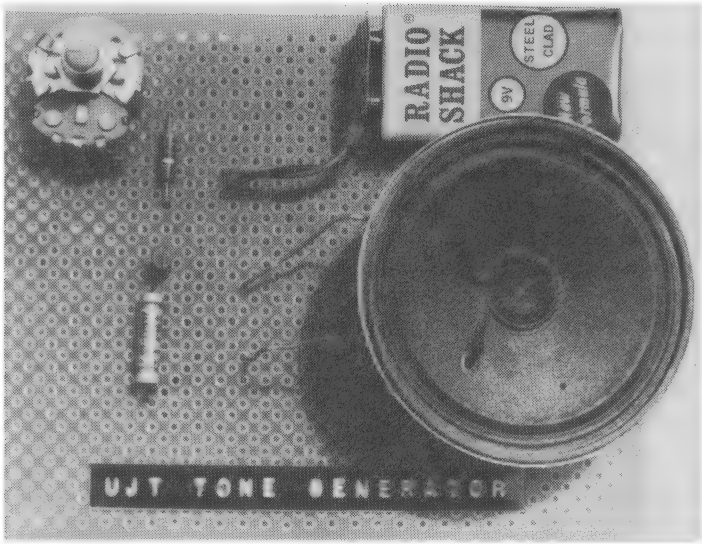


Fig. 7-22. Completed UJT tone generator.

Rotate the potentiometer's shaft to change the tone's frequency. If an oscilloscope is available connect it to the speaker terminals to see the waveform across the speaker coil. A series of spikes will be seen on the screen. The capacitor's charging cycle can be seen with either an oscilloscope or a high input impedance voltmeter.

When the tone generator is operating properly, it can be used for a variety or practical applications.

Going Further

The simplest application for the UJT tone generator is as a code-practice oscillator. All that is required to use the tone generator for this purpose is a low cost practice key. The key is available for less than a dollar. When the tone generator is used as a code practice oscillator, the frequency control should be set to obtain a comfortable tone.

To use the oscillator as an indicator or warning tone generator it's a good idea to enclose the circuit in a small metal or plastic box. Whichever is used, provisions will have to be made for the speaker's output. This is easily accomplished by drilling a concentric array of holes into the box where the speaker will be mounted. Be sure to use an on-off switch if the circuit is installed in a box. Also, for convenience mount the potentiometer (R1) in a ⅜-inch hole bored into the box.

In operation as a warning tone generator it may be a good idea to solder two wires to the switch terminals and run them outside the box. When the wires are touched together the switch is bypassed and the oscillator is turned on. The wires can be connected to the relay contacts of a circuit like the unijunction timer described in the previous chapter, or connected to a remote switch.

AUDIO AMPLIFIER

One of the most useful circuits is the amplifier. Transistors are particularly well suited to amplifier applications since their power consumptions is low and their size is small.

The amplifier described here is distinguished by its ability to amplify audio signals from a high impedance source, such as a crystal microphone. These microphones are somewhat less expensive than most other types and are popular with experimenters.

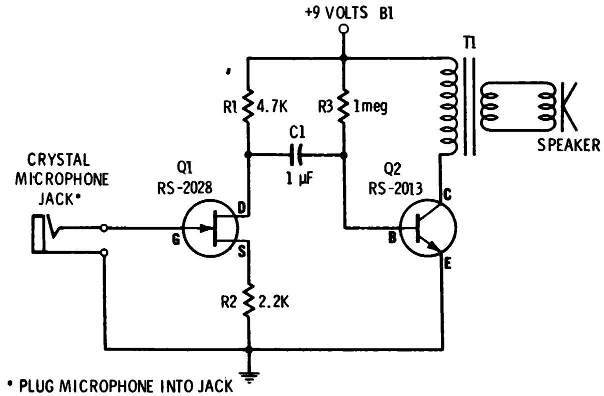


Fig. 7-23. Audio amplifier circuit diagram.

While the amplifier described here is used to drive a small speaker, it can also be used to operate an earphone. Other variations are also possible and some will be described later.

How It Works

Operation of the amplifier can be understood by referring to the circuit diagram in Fig. 7-23. In operation, sounds picked up by the crystal microphone are converted into representative electrical fluctuations. The signal is passed to the gate of Q1, an n-channel field-effect transistor. Q1 gives the amplifier its high input impedance.

The signal is next coupled through blocking capacitor C1 to Q2, a high gain audio amplifier transistor. Q2 amplifies the signal and passes it to output transformer T1. The transformer impedance matches the output of Q2 to a small speaker. Depending on the gain of Q2, the original microphone signal is amplified up to several hundred times.

As with most high gain audio amplifiers with a microphone input and speaker output, it is very easy to generate an acoustical feedback by merely placing the microphone near the speaker. Feedback occurs when naturally occurring sounds picked up by the microphone are amplified and passed on to the speaker. The sound passes back into the microphone and the cycle repeats itself. The result is a high frequency audio tone which can be made to vary in frequency, somewhat, by moving the microphone toward and away from the speaker.

Circuit Assembly

The prototype high input impedance audio amplifier is assembled, using the parts in Table 7-7, on a perforated board, as shown in Figure 7-24. Begin assembly by boring a ¼-inch hole for the microphone jack. Install the jack and secure it in position with a mounting unit.

Next, install Q1, R1, and R2 and solder their leads to one another as indicated in the circuit diagram of Fig. 7-23, and the pictorial of Fig. 7-25.

A 1-μF capacitor was used for C1 in the prototype circuit. Actually, any value between about 0.1 μF and 10 μF should

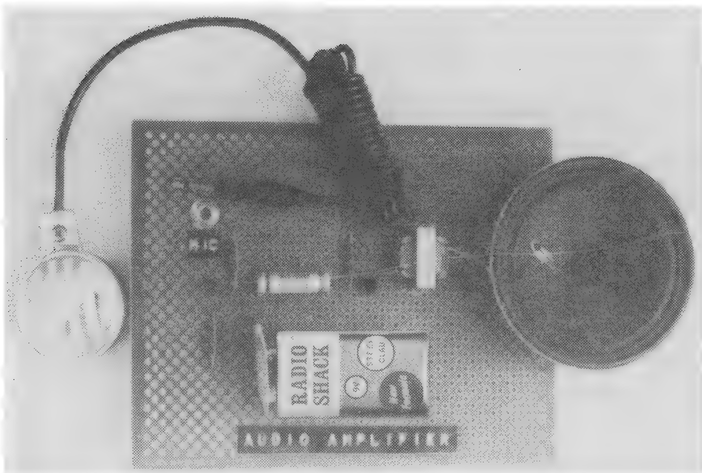


Fig. 7-24. Assembled audio amplifier.

Table 7-7. Audio Amplier Parts List

Item	Description
B1	9-volt battery
C1	1-μF capacitor
R1	4.7K resistor
R2	2.2K resistor
R3	1-megohm resistor
J1	Miniature jack
Q1	FET (RS-2028)
Q2	Npn transistor (RS-2013)
T1	Miniature transformer (1000-ohm primary and 8-ohm secondary)
Speaker	8 ohms
Misc	Crystal microphone, perforated board, battery clip, wire, solder

give similar results. Install C1 between the drain of Q1 and the base of Q2 and solder its leads in position. Install R3 and solder it in place. Then solder the battery clip in place.

Finally, install the output transformer by slightly enlarging two perforations ¾-inch apart so that the transformer's mounting tabs can be inserted in place. Bend the tabs outward

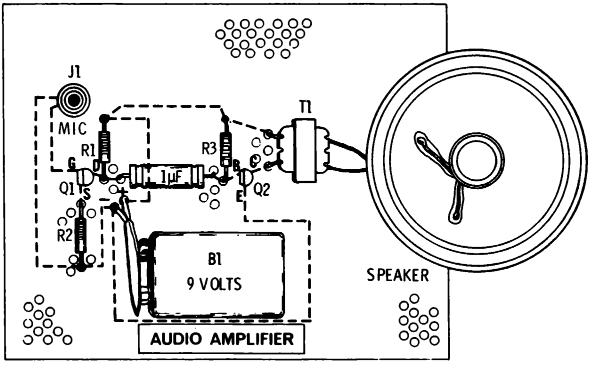


Fig. 7-25. Audio amplifier pictorial.

on the back side of the board so that the transformer is secured in place, and insert its primary leads through holes in the board. The primary leads are colored green, red, and white. The red lead is not used and can be cut off. Solder the green lead to the collector of Q2 and the white lead to the positive battery connection. Then solder the black and the white transformer secondary leads to the speaker. The circuit should now be ready for testing.

Testing and Operation

Recheck all wiring to make sure the amplifier is properly assembled. Pay close attention to the transistor leads.

When the wiring has been checked, plug a crystal microphone into the input jack and insert a 9-volt battery into the battery clip. When the microphone is brought near the speaker, a shrill tone should be heard from the speaker. This is the audio feedback described earlier. If the tone is heard move the microphone away from the speaker until the tone ceases, and speak into the microphone. Your amplified voice will be heard coming from the speaker. If the feedback tone is not heard when the microphone is placed near the speaker, disconnect the battery and recheck the wiring.

The gain of Q2 is so high that the amplifier may sometimes oscillate without the microphone being near the speaker. This kind of oscillation can be caused by disorganized wiring on the lower side of the board providing a feedback path. The problem is cured by reorienting the wiring so that it is more point to point and less disorganized.

Going Further

This basic audio amplifier can be used as an experimental device or for its intended purpose. Experimental applications include various types of tone generators and general amplifier applications requiring a very high input impedance. In the former role, the feedback provided by a closely spaced speaker and microphone gives a tone generating capability. More consistent results can be had, however, by disconnecting the microphone and encouraging oscillation by permitting some of the circuit wires to overlap one another. The wires of course, must be insulated or the amplifier may be damaged.

In the prototype amplifier, the feedback necessary to sustain oscillation could be easily generated by connecting a clip lead to the unused (red) primary lead on the transformer and allowing the other end of the clip lead to be brought near the microphone jack. Depending on whether the lead was held by the hand or clipped to a plastic insulator when brought near the jack, an impressive variety of tones could be generated.

In applications requiring a high input impedance, the microphone jack is used as the input point. For example, a high impedance phono cartridge can be connected to the amplifier in this manner. The amplifier can also be used to follow a signal through a piece of equipment during troubleshooting.

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